Our Changing Planet

The U.S. Global Change Research Program for Fiscal Year 2010

A Report by the U.S. Global Change Research Program
and the Subcommittee on Global Change Research

A Supplement to the President's Budget for Fiscal Year 2010

U.S. GLOBAL CHANGE RESEARCH PROGRAM AND SUBCOMMITTEE ON GLOBAL CHANGE RESEARCH

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This document describes the U.S. Global Change Research Program (USGCRP) for FY 2010. It provides a summary of the achievements of the program, an analysis of the progress made, and budgetary information. It thereby responds to the annual reporting requirements of the U.S. Global Change Research Act of 1990 (Section 102, P. L. 101-606). It does not express any regulatory policies of the United States or any of its agencies, or make any findings of fact that could serve as predicates for regulatory action. Agencies must comply with required statutory and regulatory processes before they could rely on any statements in this document or by the USGCRP as a basis for regulatory action.

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First Draft - September 14, 2009

September, 2009

Members of Congress:

LETTER TO MEMBERS OF CONGRESS GOES HERE

Sincerely,

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First Draft - September 14, 2009

GUIDING VISION

A nation and the global community empowered with the science-based knowledge to manage the risks and opportunities for humans and for the planet, of change in the climate and related environmental systems.

Climate plays an important role in shaping the environment, natural resources, infrastructure, economy, and other aspects of life in all countries of the world. Therefore, variations and changes in climate can have substantial environmental and socioeconomic implications. The U.S. Global Change Research Program (USGCRP) was mandated by Congress in the Global Change Research Act of 1990 (P.L. 101-606, 104 Stat. 3096-3104) to improve understanding of uncertainties in climate science, expand global observing systems, develop science-based resources to support policymaking and resource management, and communicate findings broadly among scientific and stakeholder communities. In 2002, the Climate Change Science Program (CCSP) was established, incorporating the USGCRP and integrating new elements into the program. The CCSP title was discontinued in 2009 but the structure and approach continues to provide much of the basis for the FY 2010 budget and initiates the restructuring and broadening envisioned for the revitalized USGCRP.

Climate research conducted over the past several years indicates that most of the global warming experienced in the past few decades is very likely due to the observed increase in greenhouse gas concentrations from human activities.[1] Research also indicates that the human influence on the climate system is expected to increase. It is therefore essential for society to be equipped with the best possible knowledge of climate variability and change so that we may exercise responsible stewardship for the environment, lessen the potential for negative climate impacts, and take advantage of positive opportunities where they exist. The importance of these issues and the unique role that science can play in informing society's responses give rise to the program's guiding vision that continues under the USGCRP.

The USGCRP carries out its mission through four core approaches: scientific research, observations, decision support, and communication. These approaches build upon scientific advances of the last few decades and are deepening our understanding of the interplay of natural and human-caused forces, their implications, and response options. The program places particular emphasis on developing information to facilitate comparative analysis of different approaches for adapting to and mitigating climate change. The program also promotes capacity development among scientists and information users—both in the developed and the developing world—to address the interactions between climate change, society, and the environment.

INTEGRATING CLIMATE AND GLOBAL CHANGE RESEARCH

Thirteen departments and agencies of the U.S. Government participate in the USGCRP. Representatives from each of these departments and agencies comprise the Subcommittee on Global Change Research (SGCR) of the Committee on Environment and Natural Resources (CENR), which is responsible for steering USGCRP. These departments and agencies include:

- Department of Agriculture (USDA)

MISSION

Facilitate the creation and application of knowledge of the Earth's global environment and its human effects through research, observations, decision support, and communication.

- Department of Commerce
  - National Oceanic and Atmospheric Administration (NOAA)
  - National Institute of Standards and Technology (NIST)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Health and Human Services (HHS)
- Department of the Interior/U.S. Geological Survey (DOI/USGS)
- Department of State (DOS)
- Department of Transportation (DOT)
- Agency for International Development (USAID)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Smithsonian Institution (SI)

In addition, the Executive Office of the President and other related programs have designated liaisons that participate on the SGCR, including:

- Office of Science and Technology Policy (OSTP)
- Council on Environmental Quality (CEQ)
- Office of Management and Budget (OMB)
- Climate Change Technology Program (CCTP)
- Office of the Federal Coordinator for Meteorology (OFCM)

Appendix A, "The U.S. Global Change Research Program Participating Agencies," contains information about the specific missions and roles of each agency participating in the USGCRP.

Appendix B, "U.S. Global Change Research Program FY 2010 Budget Tables," contains budgetary analyses of the program grouped by agency as well as a program-wide interagency crosscut grouped by the strategic goals and research elements as described in the *Strategic Plan for the U.S. Climate Change Research Program* published in July 2003.[2]

Appendix C, "Glossary and Acronyms," provides definitions of key terms and acronyms used in the text of this document.

The USGCRP is responsible for coordinating and integrating scientific research on global environmental variability and change sponsored by these agencies to take advantage of their unique approaches and missions, and to encourage research that leads to expanded and new results. Thus, the program helps to catalyze research that goes beyond individual agency missions to address overarching national objectives and to achieve results that no single agency, or small group of agencies, could attain. A significant challenge that arises from working across many agencies is integrating climate and global change research to develop a comprehensive view of climate change and its potential significance.

The USGCRP relies not only on the agency programs stated in its budget crosscut, but also on agency activities that are not formally included in the USGCRP budget. Examples of these directly related activities involving multiple agencies are networks and satellite observations. Satellite mission collaborations include joint NASA and USGS implementation of the Landsat Data Continuity Mission scheduled for late 2012, and the tri-agency (NOAA, DOD, NASA) National Polar-Orbiting Operational Environmental Satellite System. Without input from activities such as these, the USGCRP would be unable to fulfill its mission.

The USGCRP is closely allied with other major interagency programs that observe and study particular aspects of the Earth system and related societal dimensions. Foremost among these is the CCTP, which develops and studies technological options for responding to climate change. A key observational linkage is with the U.S. Integrated Earth Observation System, which is part of the international Global Earth Observation System of Systems (GEOSS). Collaboration and coordination among Federal agencies associated with ocean science and policy is coordinated via the National Science and Technology Council's Committee on Environment and Natural Resources through its Joint Subcommittee on Ocean Science and Technology (JSOST) and its Subcommittee on Global Change Research. Connections to programs such as these allow the USGCRP and its partners to leverage their resources to derive mutual benefits from advances in any one program.

Program Management

The USGCRP's coordination of scientific research is accomplished through the research elements described in the following section. The management

approach as described in the *2003 Strategic Plan* integrates the planning and implementation of individual climate and global change research programs of the participating Federal agencies and departments to reduce overlaps, identify and fill programmatic gaps, and synthesize products and deliverables generated under the auspices of the USGCRP. Five mechanisms are used to achieve this management approach:

- *Executive Direction* – The CENR and SGCR are responsible for overall priority setting, program direction, management review, and accountability to deliver program goals.
- *Agency Implementation* – USGCRP participating departments and agencies are responsible for conducting research, developing modeling tools, developing and operating observing systems, and producing USGCRP-required products, often in collaboration with interagency working groups.
- *Interagency Planning and Implementation* – Several interagency working groups, including one for each research element, are responsible for coordinating planning and implementation to align agency programs with USGCRP priorities.
- *External Guidance and Interaction* – External advisory groups and organizations, including the National Academies (see section below), provide external guidance, oversight, and interactions to ensure scientific excellence, credibility, and utility.
- *Program Support* – The USGCRP Office provides staffing and day-to-day coordination of USGCRP-wide program integration, strategic planning, product development, and communications.

Coordinating Research Elements

Efforts to foster integration occur on many levels. One is improving coordination of scientific research and the flow of information through interdisciplinary and interagency working groups focused on each of seven main research elements of the program plus a number of crosscutting activities or themes. The program's research elements currently include atmospheric composition, climate variability and change, the global water cycle, land use and land cover change, the global carbon cycle, ecosystems, and human contributions and responses to environmental change. Chapters 3 to 15 of the *2003 Strategic Plan* contain more detailed discussions of the discipline-specific research elements, as well as elements that cut across all areas of the program.

A brief summary of each of these research and crosscutting elements is provided below, as well as a few highlights of planned activities.

Integrating research and observational approaches across disciplinary boundaries is essential for understanding how the Earth system functions and how it will change in response to future forcing. This is due to the interconnections among components of the Earth system, which often relate to each other through feedback loops. Interdisciplinary interactions in USGCRP are scaled to the nature of the problem. In some cases, the necessary science may be conducted within a small set of disciplines, such as those required to improve understanding of soil biogeochemical processes. In other cases, highly interdisciplinary and multi-scale approaches are required, such as in the case of making projections about the future state of the Earth system and analyzing their implications. In this case, expertise ranging from the social sciences to atmospheric dynamics and chemistry to oceanography to the biological sciences is required. Examples of interdisciplinary research are the coordinated planning and operation of intensive studies of processes in high-latitude and polar regions that were recently conducted as part of the International Polar Year, recognizing these regions as sensitive barometers of environmental change.

Interdisciplinary research is only one aspect of the integration facilitated by the USGCRP. Integration in the USGCRP also refers to the steps being taken to create more seamless approaches between the theory, modeling, observations, and applications that are required to address the multiple scientific challenges being confronted by the USGCRP. Finally, integration in the USGCRP also refers to the enhancement of

cooperation across agencies toward meeting the objectives articulated in the *2003 Strategic Plan*.

NRC Study *"Restructuring Federal Climate Research to Meet the Challenges of Climate Change"*

In a highly distributed program such as the USGCRP, it is often a challenge to develop and maintain a cohesive perspective, ensuring that key components or interactions of the integrated Earth system are not overlooked. To help address this challenge, the program has often sought guidance from the National Academies. The program provided funding to a National Research Council (NRC) committee to give high-level, independent, integrated advice on its strategy and evolution. On 26 February 2009, the NRC Committee on Strategic Advice on the U.S. Climate Change Science Program released a report entitled *"Restructuring Federal Climate Research to Meet the Challenges of Climate Change."*[3] This report was the second task of the NRC committee; the report of the first task was released in 2007.[4] In general, the committee found that the program, and its related research activities, will help provide the scientific foundation needed to answer the urgent needs of society in responding to climate change. The committee found that the vision of the current program, as articulated in the *2003 Strategic Plan*, remains on target and is even more relevant to the future of the program than it has historically been. In concert with the NRC thinking, the USGCRP continues with the vision of the program. In order to address the articulated vision, the committee recommended that the future program become broader in scope. The future climate change program will play a key role by building knowledge, through sound science and incontrovertible observations, that will inform decisionmaking at various levels. However, meeting the needs of decisionmakers will require a transformational change in how climate change research is organized at the Federal level and incorporated into public policy.

The committee's six top priorities, cast as actions for the restructured climate change research program, are:

- Reorganize the program around integrated scientific-societal issues to facilitate crosscutting research focused on understanding the interactions among the climate, human, and environmental systems and on supporting societal responses to climate change.
- Establish a U.S. climate observing system, defined as including physical, biological, and social observations, to ensure that the collection of data needed to address climate change is initiated or continued.
- Develop the science base and infrastructure to support a new generation of coupled Earth system models to improve attribution and prediction of high impact regional weather and climate, to initialize seasonal to decadal climate forecasting, and to provide predictions of impacts affecting adaptive capacities and vulnerabilities of environmental and human systems.
- Strengthen research on adaptation, mitigation, and vulnerability.
- Initiate a national assessment process with broad stakeholder participation to determine the risks and costs of climate change impacts on the United States and to evaluate options for responding.
- Coordinate Federal efforts to provide climate services (scientific information, tools, and forecasts) routinely to decisionmakers.

The report described program restructuring in general terms, with an emphasis on the program being more responsive to the information needs of stakeholders. Central elements of the recommended approach include basic research, user-driven research, climate services, and stakeholders. Modeling, observations, and data span the first three central elements. Communications, national assessment, and decision support integrate all four central elements.

The report also included broad recommendations for future funding priorities and approaches for improving program management. The recommendations of this report are being given careful consideration by the program.

GOALS AND ANALYSIS OF PROGRESS TOWARD THESE GOALS

This annual report is structured around the five goals described in the *2003 Strategic Plan* . These goals address understanding the components of the Earth's varying environmental system, with a particular focus on climate; understanding how these components interact to determine present conditions;

understanding what drives these components; understanding the history of global change and projecting future change; and understanding how knowledge about global environmental variability and change can be applied to present-day and future decisionmaking.

This section provides an overview of the progress made toward achieving these goals in the *2003 Strategic Plan* 12 to 18 months prior to the preparation of *Our Changing Planet 2010*. Because of the breadth and width of climate research funded by the U.S. Government, this overview only provides a general summary of some of the many climate change research activities covered under the USGCRP umbrella.

In the past decade, the primary focus of U.S. climate research has been on the goals that emphasize understanding the global climate system through observations, identifying the various components of the global climate system, understanding how the various components interact to drive the climate system, and working toward developing predictive tools that identify near- and long-term climate variability. As we continue to make progress toward a better understanding of the global climate system, and in response to the recommendations of the NRC program restructuring study, greater emphasis is being placed on the goals emphasizing understanding system adaptability to climate change and managing risks and exploring opportunities associated with climate variability and change.

The following are recent examples of progress contributing to each of these five goals, resulting from coordinated research activities in many disciplines conducted by or supported across the participating USGCRP agencies. In all of these areas, USGCRP has functioned to facilitate interagency cooperation and coordination within the U.S. Government toward meeting the five goals described in the *2003 Strategic Plan* .

The research element and crosscutting element chapters of *Our Changing Planet FY 2010* give a brief summary of the significant array of scientific evidence that human activities are responsible for recent global warming. Recent studies have (1) shown through observations that warming of the climate is unequivocal; (2) the global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases; and (3) these emissions come mainly from the burning of fossil fuels (coal, oil, and gas), with important contributions from the clearing of forests, agricultural practices, and other activities. These conclusions emphasize USGCRP's urgent mission of interagency cooperation and coordination. In order to continue to improve understanding of ongoing and future changes, in particular to provide information to support decisionmaking, the need for sustained satellite and climate observations is underscored. These observational activities must be coupled with robust modeling and analysis, as well as research on impacts, adaptation, and vulnerability to global environmental variability and change.

Examples of recent progress toward the five goals are briefly summarized below.

Goal 1. Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.

Over the past three decades, a combination of ground and global satellite observations together with Earth system models conducted by the participating USGCRP agencies have resulted in

remarkable progress in first documenting and subsequently understanding the components of the global climate system and how these components interact. These multi-agency activities have resulted in basic information that has led to the formulation of numerical simulation models required to further understanding of Earth's climate system. Numerical climate simulation models using observed radiative forcing provide the means to anticipate future climate, manage future climate risks, and explore opportunities related to climate variability and change. Model simulations also identify shortcomings in the climate observations, thereby providing the feedback needed to improve the cycle of measurement and modeling. A few illustrations of this important work are given below.

Improved Approaches to Hydrological Modeling. Major uncertainties in hydrological modeling stem from difficulties the climate models have in providing reliable information on hydrologic forcing by incoming radiation and changing precipitation. Researchers have developed an ensemble method for generating atmospheric forcing fields for assessing the uncertainty in simulated hydrologic responses. These studies showed how static surface parameters such as topography affect patterns of hydrologic uncertainty. The information gained regarding the signature of topography seen in soil moisture patterns provides valuable insights that climate modelers can use to improve results at model locations where rough or complex topography presents a major modeling challenge.

Reconstructed Surface Temperatures for the last 2,000 Years.[5] Using a greatly expanded set of proxy data and recently updated instrumental data, USGCRP researchers have reconstructed surface temperature at hemispheric and global scales for much of the last 2,000 years. These reconstructions were suggested in a recent NRC report[4] summarizing current scientific information on the temperature record for the past two millennia. The lack of widespread instrumental climate records before the mid-19th century necessitates the use of natural climate archives or "proxy" data such as tree rings, corals, ice cores, and historical documentary records to reconstruct decadal-to-centennial climate changes for past centuries. Complementary methods that have been thoroughly tested and validated with model simulation experiments have been used in this study for both the proxy data and the data since the mid-19th century. Results of this study extend previous conclusions that recent Northern Hemisphere surface temperature increases are probably anomalous in a long-term context. Recent warmth appears anomalous for at least the past 1,300 years whether or not tree ring data are used. If tree ring data are used, the conclusion can be extended to at least the past 1,700 years, but with additional strong caveats. The reconstructed amplitude of change over past centuries is greater than previously reported, with somewhat greater medieval warmth in the Northern Hemisphere, albeit still not reaching recent levels.

Consistency of Modeled and Observed Temperature Trends in the Tropics.[6] A Synthesis and Assessment Product[7] identified potentially serious inconsistencies between modeled and observed trends in tropical surface and tropospheric temperatures. Earlier satellite and observational data had suggested that the tropical surface had warmed more than temperatures aloft, while climate models consistently showed greater warming above the surface in response to human-caused increases in well-mixed greenhouse gases. A new study finds that there is no longer a serious discrepancy between modeled and observed trends in tropical tropospheric temperatures. There are two primary reasons for the reconciliation: 1) corrections in buoy and satellite information have led to slightly reduced surface temperature trends, and 2) corrections to recently developed satellite and radiosonde datasets now show greater warming in the tropical troposphere.

Goal 2. Improve quantification of the forces bringing about changes in the Earth's climate and related systems.

To understand the Earth's coupled ocean-atmosphere-land climate system, it is necessary to understand the abiotic and biotic processes that drive this system. These causes of climate change are defined as the "forcing" factors and include greenhouse gases, land cover change, volcanoes, air pollution and aerosols, and solar variability. The following paragraph gives one example of the program's important contributions in this area.

Study Shows Strong Sensitivity of Late 21st-Century Climate to Short-Lived Air Pollutants.[8] USGCRP researchers have examined the impact of projected

changes in the emissions of four short-lived air pollutants (ozone, black carbon, organic carbon, and sulfate) on future climate. In the near term, the researchers find that their effects on global radiative forcing nearly cancel (see Figure 1). However by 2100, the projected decrease in cooling by sulfate aerosol and increase in warming by black carbon lead to a significant net surface warming (0.4°C globally, 1.5–2.0°C in the U.S. summer). The results also show a decrease in central U.S. precipitation and soil water. The global average increase in radiative forcing is projected to be approximately 1 W m^{-2}, with regional patterns of warming that are similar to the patterns for the longer-lived greenhouse gases.

Goal 3. Reduce uncertainty in the projections of how the Earth's climate and related systems may change in the future.

USGCRP research has led to significant improvements in our ability to produce estimates of future Earth climates on time scales of years to centuries, using numerical simulation models initialized with measured radiative forcing obtained from ground and satellite observations. The first example given below shows the progress made in improving understanding of the effect of land use on the regional climate of the southeastern United States. The second example illustrates improved understanding of the role of increased greenhouse

Short-Lived Air Pollutants Influence Temperature Trends

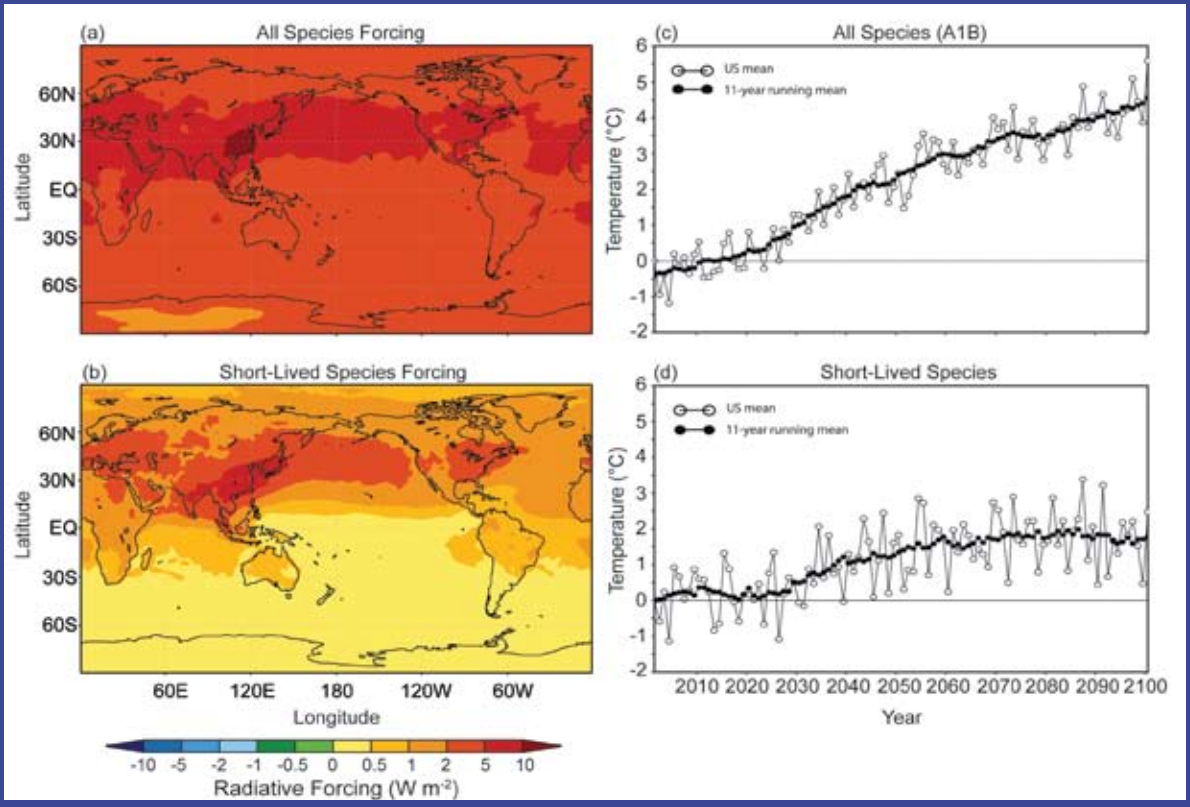


Figure 1: Model simulations of changes in radiative forcing (W m^{-2}) from 2000 to 2100 for all greenhouse gases (panel a, top left) and short-lived species only (panel b, bottom left). The short-lived species (sulfate, black carbon, tropospheric ozone, and organic carbon) exhibit a northern mid-latitude maximum. The right-hand panels show the simulated time series of summer average surface air temperature changes (°C) relative to the year 2001 for the continental United States, showing the increasing contribution from short-lived species after the year 2030 (panel d, lower right). *Credit: H. Levy II, M.D. Schwarzkopf, L. Horowitz, V. Ramaswamy, and K.L. Findell, NOAA/Geophysical Fluid Dynamics Laboratory (reproduced from* **Journal of Geophysical Research** *with permission from the American Geophysical Union).*

gas concentrations on regional climate, particularly the hydrology of the western United States.

Temperature Changes in Response to Changing Land Use in the Southeastern United States.[9] In the southeastern United States, the conversion of abandoned agricultural land to forested ecosystems via both ecological succession and plantation forestry has been a dominant feature of land use change since post-Civil War reconstruction and the 1950s, respectively. Over the next 40 years, the area of land "populated" by pine plantations within this region is projected to nearly double given the expected economic demand for forestry products, while agricultural acreage is expected to decline by one-third and upland hardwood forested area by a lesser extent. Such conversions would be expected to significantly alter air and surface temperatures due to changes in surface reflectance of sunlight (albedo) accompanying the vegetative changes. While incident sunlight is high in this region compared to other forested regions within the United States, albedo is not the only factor affecting temperature. Changes in atmosphere-ecosystem energy exchange (evapotranspiration) and canopy height (a surrogate for roughness effects) affect temperature through evaporative cooling. To test the relative importance of these competing factors, researchers conducted a field experiment and showed that conversion of abandoned agricultural sites to pine plantations and hardwood forests under similar climatic and soil conditions results in surface cooling trends, that is, increased evaporative cooling and roughness effects counteract the warming due to albedo changes.

Water Resources in the Western United States.[10,11] A regional, multivariable climate-change detection and attribution study was performed using a high-resolution hydrologic model forced by global climate models to identify and explain causes of changes in the western U.S. water cycle. The results suggest that up to 60% of the climate-related trends in river flow, winter air temperature, and snowpack between 1950 and 1999 were human induced. A second study estimated future changes in water supply in the Colorado River system under the assumption that current operating practices continued unchanged. That study showed that live storage (the volume of the lake that varies with lake level) in Lakes Mead and Powell would be significantly limited in the next few decades, due to the effects of climate change, natural climate variations, and the status of the reservoir system at the time of the study. The timing of the resulting impacts found in this study is subject to some uncertainty, but the study identifies a major problem for future water management of the Colorado River system. A third study applied a high-resolution climate model to investigate future changes in snowmelt-driven runoff (SDR) over the western United States. It found that by the late 21st century, warming due to increasing greenhouse gas concentrations could cause SDR to occur as much as two months earlier than at present. The combination of reduced snowpack and early SDR is likely to lead to substantial modifications in the western hydrological cycle, with potential impacts including increased winter and spring flooding; changes in lake, stream, and wetland ecology; and reduced river flow and natural snow and soil storage.

Goal 4. Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global change.

A key purpose of the USGCRP is to understand potential effects of changes in the Earth's climate system on natural ecosystems, managed ecosystems, and human systems through a coordinated program of ecological observations, experimental research, and numerical simulations made possible by advanced observations and experimentation being planned and implemented by the USGCRP. This goal not only addresses water, air quality, health, human infrastructure, and agriculture, it also addresses the effects of climate change on natural terrestrial and oceanic ecosystems as shown in the two examples that follow.

Mapping Global Ocean Biomes.[12,13] Ocean biomes represent large areas of the seascape that operate with similar physical and biological processes. Ocean biomes have historically been difficult to map because they are temporally and spatially dynamic. However, satellite data combined with objective classification algorithms now allow us to map ocean biomes from space in near real-time (see Figure 2). In addition, a new ecosystem-specific, multi-scale model provides a synthesis of human causes of ecological change and maps human impacts on 20 marine ecosystems, showing that multiple causes of ecological change strongly affect approximately 40% of the world's

ocean ecosystems. These ocean biome maps provide the framework needed for detecting and quantifying large-scale ecosystem-level changes in response to human impacts and climate change.

Warming Temperatures, Food Production, and Agricultural Security in Africa.[14] Since 1980, the number of undernourished people in eastern and southern Africa has more than doubled. Analyses of station data and satellite observations of precipitation have identified another problematic trend: main growing-season rainfall has diminished by approximately 15% in food-insecure countries clustered along the western rim of the Indian Ocean. Will this trend persist? The current moisture deficit has been traced back to higher temperatures in the Indian Ocean, which in turn are likely due to warming caused by human-induced increases in soot and greenhouse gases. This leads to the conclusion that further warming may cause further decline in rainfall in the region. The potential impacts of the observed precipitation and agricultural capacity trends were modeled as a function of rainfall, population, cultivated area, seed, and fertilizer use. Persistence of current tendencies may result in a 50% increase in undernourished people in this area by 2030. On the other hand, modest increases in per capita agricultural productivity could more than offset the observed precipitation declines.

Ocean Biomes Mapped from Satellite

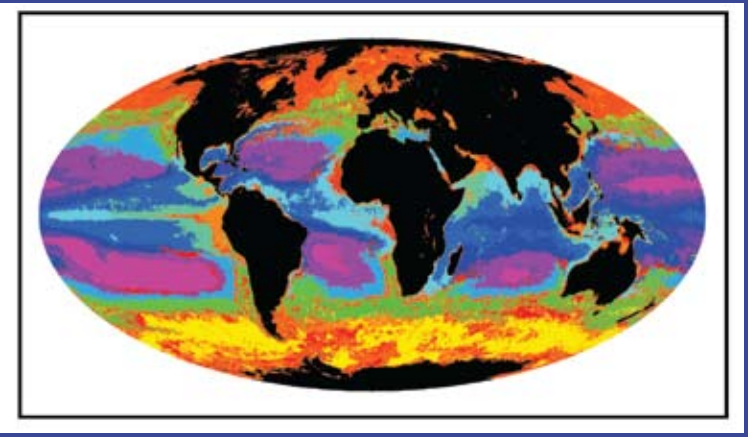


Figure 2: Novel mathematical approaches and satellite imagery allow the mapping of ocean biomes. The equal area projection map shown is for the year 2006 and is constructed using ocean color and sea surface temperature data acquired by NASA's MODIS-Aqua. Colors identify distinct classifications (province types) and do not represent the value of any of the predictor variables. *Credit: M.J. Oliver, Rutgers University, and A.J. Irwin, Mount Allison University (adapted from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

Goal 5. Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

A critical responsibility for the program is to encourage the USGCRP agencies to use improved understanding of climate processes and numerical simulation models to manage risks and identify opportunities related to climate variability and change.

One example of progress toward Goal 5 is an assessment of climate information for watershed management associated with wildfire in the western United States.[15] The use of climate forecast information in fire management began because decisionmakers within the wildland fire management community were open to new information, due to legal challenges, public pressure, and a "landmark" wildfire season in 2000. The National Fire Plan (2000) and its associated 10-year Comprehensive Strategy reflected an increased receptiveness for new ways of coping with vulnerabilities; it called for a community-based approach to reducing wildland fires that is proactive and collaborative. Improvements in climate forecasting, and research on interactions between climate and wildland fire occurrence, have generated opportunities for improving use of seasonal climate forecasts by fire managers. This finding was one of the case studies forming part of Synthesis and Assessment Product 5.3, *Decision-Support Experiments and Evaluations using Seasonal-to-Interannual Forecasts and Observational Data: A Focus on Water Resources*. The study found that fire managers could now better anticipate annual fire risk, including potential damage to watersheds over the course of the year. Climate information can help managers plan for fire risk in the context of watershed management and post-fire impacts, including impacts on

water resources. One danger is inundation of water storage and treatment facilities with sediment-rich water, creating potential for significant expense for pre-treatment of water or for facilities repair. Post-fire runoff can also raise nitrate concentrations to levels that exceed the Federal drinking water standard. Mudslides and soil stability are also a concern after wildland fire. The project, initiated in 2000, continues to produce annual fire-climate outlooks. The interactions between climate scientists and fire managers clearly demonstrated the utility of climate information for managing watershed problems associated with wildfire. Climate forecast information in fire management is now part of accepted practice by agencies, and has produced spin-off activities managed and sustained by the agencies and new participants.

DECISION SUPPORT: INFORMATION TO SUPPORT POLICY DEVELOPMENT AND ADAPTIVE MANAGEMENT

The USGCRP sponsors and conducts research that is ultimately related to policy and adaptive management decisionmaking. The USGCRP's decision support approach is guided by several general principles, including:

- Early and continuing involvement of stakeholders
- Explicit treatment of uncertainties
- Transparent public review of analysis questions, methods, and draft results
- Evaluation of lessons learned from ongoing and prior decision support and assessment activities.

Synthesis and Assessment Products

As noted previously, the USGCRP has generated Synthesis and Assessment Products that integrate research results focused on key issues and related questions frequently raised by decisionmakers. Current evaluations of the science can be used to inform public debate, policy development, and adaptive management decisions and to define and set the future direction and priorities of the program. The Synthesis and Assessment Products constitute an important new form of topic-driven integration of U.S. global change assessment efforts. These Synthesis and Assessment Products are U.S. Government

reports, subject to the provisions of the Information Quality Act (Section 515 of the Treasury and General Government Appropriations Act of 2001) and the Federal Advisory Committee Act Amendments of 1997 (PUB. L. 105-153, SEC. 2(A), (B), DEC. 17, 1997, 111 STAT. 2689.).

The Synthesis and Assessment Products were generated by researchers in a process that involved review by experts, public comment from stakeholders and the general public, and final approval by the departments/agencies involved in the USGCRP. Formal endorsement of the products by the Federal Government enhances their value for decisionmakers and the public at large. A list of the 21 Synthesis and Assessment Products, arranged by goal and providing title, date of completion, and brief description is given in Chapter 8 of this report. The 21 products were completed within or prior to the reporting period of *Our Changing Planet FY 2010*.

OUTLINE OF RESEARCH AND CROSSCUTTING ELEMENT ACTIVITIES

The USGCRP participating agencies coordinate scientific research through a set of linked interdisciplinary research elements and crosscutting activities that encompass a wide range of interconnected issues related to climate and global change. Chapters 3 to 15 of the *2003 Strategic Plan* contain more detailed discussions of the research elements as well as activities that cut across all areas of the program. This report focuses on highlights of recent research and program plans for FY 2010.

Atmospheric Composition. The composition of the atmosphere at global and regional scales influences climate, air quality, stratospheric ozone, and precipitation, which in turn can affect

various aspects of human activities and the Earth system, such as human health and the vitality of ecosystems. Research and observational activities coordinated and supported by the USGCRP are being used to assess how human activities and natural processes affect atmospheric composition, and how that understanding may be used to inform decisionmaking in the United States and abroad for mitigation and adaptation choices. In FY 2010, emphasis will be placed on studies of aerosols and aerosol/cloud interactions in the polar environment, planning for NASA Decadal Survey missions, and elucidating the interactions of black carbon and other pollutants with climate change, especially at regional levels. Understanding the interactions between climate change and air quality and communicating these results to decisionmakers will be a priority. Special emphasis will be placed on the climate impacts of pollutants associated with aviation.

See 2003 Strategic Plan Chapter 3.

Climate Variability and Change (including Climate Modeling). Recognizing that the climate system operates seamlessly across a wide spectrum of time scales, USGCRP-supported research encompasses short-term climate variability and longer-term climate change as well as the interactions across time scales. Such interactions are critical to understanding how extreme events, such as hurricanes and droughts, may be altered by human-induced climate change. They are also important for understanding and predicting regional climate variations and change and assessing the potential for abrupt changes. Developing an improved understanding of the interactions between climate processes that may accelerate (or reduce) rates of climate change requires designing observational systems to monitor the climate system, careful process studies, and models that can reproduce past behavior and project future changes. An important research thrust is to integrate the numerous and diverse observations of the climate system into increasingly sophisticated climate models to produce internally consistent records of atmospheric, oceanic, land surface, and sea ice conditions in near real-time. These records will be used to compare current conditions with those of the past and to better understand interactions among the various climate processes. This capability will enable ongoing, scientifically based assessments of how and why the Earth system is changing over time. Climate modeling activities have a major focus on developing and applying Earth system models that will, for the first time, include an interactive carbon cycle. Climate projections performed with these models will provide a major U.S. contribution to the IPCC Fifth Assessment.

See 2003 Strategic Plan Chapters 4 and 10.

Global Water Cycle. Research associated with this element involves studies of the crucial role the water cycle plays in climate variability and change, and the influence climate has on aspects of the global water cycle on which society and nature critically depend. Through countless interactions within the Earth system, the global water cycle integrates physical, chemical, and biological processes that sustain ecosystems and influence climate and related global change. The ultimate goal of the USGCRP water cycle research is to provide a better foundation for decisions and investments by policymakers, managers, and individuals. Achieving this goal requires a program of activities that test predictions and data products in real decision contexts, demonstrate techniques and their effectiveness to potential users, and provide tools and strategies to

transfer the science from the experimental realm to operations. In FY 2010, emphasis will be placed on furthering fundamental hydrologic research to address societal needs in a changing climate. Specific projects will focus on such areas as enhancing observing and monitoring networks to provide critical hydrologic data needed for climate modeling, improving cloud-radiative and cloud-aerosol interactions and associated feedbacks in climate models, and for improving our understanding of soil moisture, streamflow, and groundwater interactions and their impacts on water resources.

See 2003 Strategic Plan Chapter 5.

Land Use and Land Cover Change. Land use and land cover are linked to climate and weather in complex ways and are critical inputs for modeling greenhouse gas emissions, carbon balance, and ecosystems. Land use and land cover change (LULCC) studies have provided critical inputs to large-scale biomass and forest cover assessments. LULCC goals for FY 2010 include reducing uncertainties in biomass estimates, understanding regional heterogeneities in observed changes, and quantifying linkages and feedbacks between LULCC, climate change, and other human and environmental components. Research that examines historic, current, and future LULCC, its drivers, feedbacks to climate, and its environmental, social, economic, and human health consequences is therefore of utmost importance and often requires interagency and intergovernmental cooperation. Research plans focus on how management practices may change as climate and conservation policies change, and on feedbacks related to environmental, social, economic, and human health.

See 2003 Strategic Plan Chapter 6.

Global Carbon Cycle. Increasing levels of atmospheric carbon dioxide (CO_2) and methane (CH_4) are major drivers of climate change. The global carbon cycle element of the USGCRP seeks to better quantify and understand the dynamics of the global carbon cycle that determine CO_2 and CH_4 fluxes and carbon storage in terrestrial and oceanic ecosystems. Carbon cycle processes depend on climate, thus linking carbon cycle and climate change analyses is critical. Carbon cycle research involves multiple disciplines and extends over a broad range of spatial and temporal scales. Major multi-agency activities include the North American Carbon Program (NACP), an effort to describe and reduce uncertainties about the North American carbon budget and underlying processes, and the Ocean Carbon and Climate Change (OCCC) Program, a research effort aimed at determining how climate change will affect the future behavior of the oceanic carbon sink. In FY 2010, NACP and OCCC will continue to integrate to better quantify and understand the roles of adjacent ocean basins in the North American carbon budget; address key issues and gaps in observations; network and system needs and uncertainties; and develop a new carbon cycle science plan with broader socioeconomic context for the next decade.

See 2003 Strategic Plan Chapter 7.

Ecosystems. This research element studies the potential effects of global change on goods and services provided by aquatic and terrestrial ecosystems, using observations, experiments, modeling, and syntheses to focus on critical emerging questions. Projects in aquatic systems are studying the effects of climate on community composition and invasive species. In terrestrial systems, research on the interactions among climate, disturbances such as fire, and human impacts is helping to understand the ways in which ecosystems will change in the future. New research topics include assessments of adaptation options and resource management strategies, integrating satellite observations with measurements and models to forecast changes in ecosystems, and studying the impacts of climate change on coastal and high-latitude ecosystems.

See 2003 Strategic Plan Chapter 8.

Human Contributions and Responses to Environmental Change. Human activities play a critical role in driving environmental change at local, regional, and even global scales. Social, economic, and cultural systems are evolving as the world continues to become more populated, urban, and interconnected than ever before. A more integrated understanding of the complex interactions between human societies and natural systems is essential for identifying various vulnerabilities to climate change, pursuing mitigation and adaptation measures in response to such change, and capitalizing on opportunities that may emerge. Basic social science research provides a foundation for understanding the "human dimensions" of global change—including studies of potential technological, social, economic, and cultural drivers of global change, and how these and other aspects of human systems may be affected by climate change. The

challenges of human dimensions research, associated with its cross-disciplinary nature and the mix of qualitative and quantitative data and analyses, are widely acknowledged. However, the need for continued progress in this area continues to grow as the need to adapt to a changing climate becomes increasingly apparent. The USGCRP's research on human contributions and responses to global change includes analyses of human drivers of change and their potential impact, societal resilience and ways of reducing vulnerability, and the effects of global environmental change on infrastructure, management of vital natural resources, and human health.

See 2003 Strategic Plan Chapter 9.

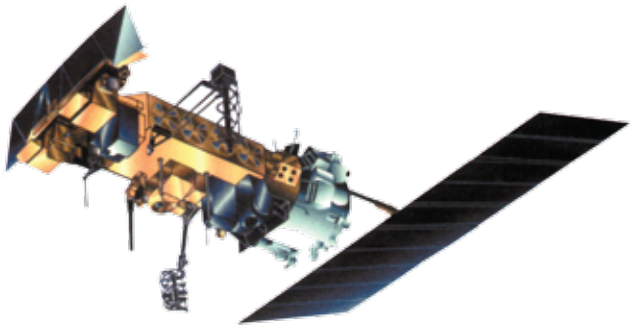
Decision Support Resources Development. Decisionmakers, including natural resource managers, policymakers, and other climate information stakeholders, need reliable, science-based information to identify, formulate policies in response to, and implement activities addressing the risks and opportunities posed by climate variability and change. The USGCRP's decision support efforts center on developing, delivering, and improving access to climate information that is relevant and useful to the program's many stakeholders, and a wide variety of the program's decision support efforts aid in achieving these objectives. The most prominent of USGCRP's recent decision support activities was the preparation of 21 Synthesis and Assessment Products that discuss specific disciplinary and sectoral climate science issues within the United States. Another important decision support activity is a series of climate science stakeholder listening sessions and targeted meetings that solicit input from climate information end users on the specific needs and challenges they face in addressing climate change at the local, regional, and national level. Such input can help shape the directions of future climate science research so that it can better meet the needs of end users.

See 2003 Strategic Paln Chapter 11.

Observing and Monitoring the Climate System. The USGCRP provides active stewardship of observations that document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society. Some of these observations are not part of the USGCRP budget (such as operational satellites like the National Polar-Orbiting Operational Environmental Satellite System) but are crucial to its success. A core USGCRP activity is U.S. participation in the broad-based strategy of the international Global Climate Observing System (GCOS) in monitoring atmospheric, oceanic, and terrestrial domains with an appropriate balance of *in situ* and remotely sensed observations. As the U.S. plan for climate observations moves forward, it strives to build on the 2004 *GCOS Implementation Plan*.[16] This plan is used by the USGCRP agencies as a blueprint for guiding GCOS-related climate observation activities that are briefly documented in Chapter 9 of this report. In 2009, the international GCOS community initiated the update of the *GCOS Implementation Plan*. As a follow-up to International Polar Year (IPY) activities conducted from 2007 to 2009, participating U.S. data centers are prepared to archive and provide access to selected IPY datasets submitted by researchers. A continuing challenge for USGCRP agencies is ensuring the long-term integrity and understandability of data products provided by remote sensing and *in situ* observing systems. Key parts of this challenge include continuing to integrate surface climate observations via the U.S. Climate Reference Network as well as in a modernized Historical Climatology Network; expanding the GCOS observing network via activities such as the Atmospheric Radiation Measurement Climate Research Facility and the GCOS Reference Upper Air Network; and support for a number of research-related satellite missions documented in Chapter 9 of this document.

See 2003 Strategic Plan Chapters 12 and 13.

Communication. USGCRP's member agencies support a broad array of communication initiatives. The USGCRP has developed a strategy and implementation plan for helping to coordinate and facilitate these activities. These efforts are intended to improve public understanding of climate change



research by disseminating the results of USGCRP activities credibly and effectively, and by making USGCRP science findings and products easily available to a diverse set of audiences. The USGCRP facilitates communication of the results of individual agencies, as well as providing coordination in communicating the results of climate activities of the Federal Government.

See 2003 Strategic Plan Chapter 14.

International Research and Cooperation. The USGCRP, through its working groups including the Interagency Working Group on International Research and Cooperation, participates in and provides input to major international scientific and related organizations on behalf of the U.S. Government and scientific community. The USGCRP also provides support to maintain the central infrastructure of several international research programs and international activities that complement USGCRP and U.S. Government goals in climate science.

See 2003 Strategic Plan Chapter 15.

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1 ATMOSPHERIC COMPOSITION

Strategic Research Questions

3.1 What are the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?

3.2 What are the atmospheric sources and sinks of the greenhouse gases other than CO2 and the implications for the Earth's energy balance?

3.3 What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality and atmospheric chemical inputs to ecosystems?

3.4 What are the characteristics of the recovery of the stratospheric ozone layer in response to declining abundances of ozone-depleting gases and increasing abundances of greenhouse gases?

3.5 What are the couplings and feedback mechanisms among climate change, air pollution, and ozone layer depletion, and their relationship to the health of humans and ecosystems?

See 2003 *Strategic Plan,* Chapter 3, for detailed discussion of these research questions.

Gases and particles in the Earth's atmosphere vary with spatial scale and with time, influencing climate, air quality, the stratospheric ozone layer, and weather. These atmospheric constituents affect human health, ecosystems, and agriculture and, therefore, are highly relevant to society. USGCRP research on atmospheric composition focuses primarily on how human activities and natural processes affect atmospheric composition, and how these changes in turn relate to societal issues. These multi-faceted issues cut across multiple disciplines and span many spatial scales. To meet these challenges, USGCRP research is a broad endeavor that involves coordinating observational studies, laboratory investigations, and modeling analyses to provide the timely, accurate, and useful scientific information needed by decision-makers nationally and internationally.

USGCRP research has led to progress in understanding the role of atmospheric composition in Earth's climate. Work has focused on the areas of the largest uncertainty in understanding how atmospheric constituents other than carbon dioxide (CO2) affect the climate. The interactions among clouds, atmospheric fine particles (or aerosols), and climate have been investigated in order to quantify

the effects of aerosols on clouds and climate. The impacts of aircraft emissions on climate have been considered in recent USGCRP research, as have the effects of wild and prescribed fires. The effects that changes in emissions have had on global aerosol and ozone concentrations, as well as their effects on climate, have also been investigated. USGCRP researchers have also made estimates of how a changing climate will affect air quality.

For FY 2010, USGCRP's Atmospheric Composition research will focus on aerosols and aerosol/cloud interactions in the polar environment through analyses of measurements from satellites, aircraft, and the surface made during the International Polar Year (spring 2007 to summer 2008). Research under the Aviation Climate Change Research Initiative will analyze the impacts of aircraft emissions on atmospheric composition and climate. Additional work focuses on developing linked air quality-climate modeling systems, future emission projections, and communicating research results to air quality decisionmakers.

HIGHLIGHTS OF RECENT RESEARCH

The following are selected highlights of recent research supported by USGCRP participating agencies.

CLOUD-AEROSOL-CLIMATE FEEDBACKS AND INTERACTIONS

International Polar Year 2008 Research.[1,2,3] In 2008, a series of observations were made from surface, balloon, aircraft, ship, and satellite platforms to better understand the causes and consequences of warming in the Arctic region. On average, this region exhibits larger warming than other latitudes across the globe. As a result of the warming, summer sea ice cover has decreased in extent by about 40% relative to the 1979 to 2000 average, and the concentration and thickness of the sea ice are also decreasing. USGCRP scientists, together with international colleagues, conducted multiple coordinated field studies in the Arctic region in 2008 to investigate the role of pollution in the changing Arctic environment. Spring measurements provided information on the impact of northern mid-latitude pollution on Arctic climate, particularly the "Arctic haze," a thick layer of aerosols formed by pollution transported into the Arctic region. Airborne observations based out of Alaska were used to investigate the possible connections between

the Arctic haze, cloud formation, and melting sea ice in the Arctic region. The relatively older aerosol pollution was compared with aerosol and trace gas pollution provided by shipboard measurements in the North Greenland and Barents Seas, closer to the pollution sources. Intensive observations of cloud and aerosol properties were also made over the North Slope of Alaska during this time period. These data will allow researchers to better understand the properties of Arctic aerosols and how they affect the processes involved in cloud formation and the surface energy budget. Airborne measurements of the Arctic haze were also made to investigate the importance of halogen chemistry to Arctic boundary layer ozone and oxidation chemistry. These coordinated measurements gave clear indications of long-range transport that could be traced back to emissions from human activities in Asia, Europe, and North America, as well as from Asian and Siberian biomass burning.

CLIMATE-RELEVANT PROPERTIES OF AEROSOLS

Sulfur Chemical Pathways in Marine Aerosol.[4] The most important gaseous aerosol precursor over the ocean is biogenic dimethyl sulfide, which, after production by phytoplankton, can be oxidized along competing pathways to end products involving sulfate or methylsulfonic acid. The competition among these pathways is significant for climate since the aerosols formed have different size and activation properties as cloud condensation nuclei and thus affect marine cloud formation. To assess these effects in a real marine aerosol, dry cloud droplet residue particles and interstitial aerosol were collected during the Marine Stratus Experiment (MASE) and the detailed chemical composition of individual particles was determined using a combination of complementary microanalysis techniques. Based on composition, morphology, and chemical bonding information, two externally mixed, distinct classes of sulfur-containing particles

were identified: chemically modified (aged) sea salt particles and secondary formed sulfate particles. This research will ultimately enhance the understanding of the processes by which clouds form over the marine areas that cover most of the Earth's surface.

Regional Pollution, Global Climate Change, and Hemispheric Transport

Impact of Global Change on U.S. Regional Air Quality.[5,6,7,8,9,10] Recent studies have provided estimates that climate change will increase summer surface ozone in polluted regions by 1 to 10 ppb (EPA's proposed new standard is 75 ppb) over the coming decades, with the largest effects in urban areas and during pollution episodes. These changes in ozone are primarily attributed to increases in temperature and increased regional-scale stagnation. Though decreases in anthropogenic ozone precursor emissions will lower U.S. ozone concentrations, some of those gains may be offset by the impact of climate change on ozone, which could make reaching national air quality standards more challenging. The effect of climate change on particulate matter is more complicated and uncertain than for ozone. This is due largely to the complex composition of particulate matter and the uncertain effects of climate change on precipitation, mixing, and ventilation.

Scientists Take Broad Look at Soot Emissions from Commercial Shipping.[11] USGCRP researchers have published the first broad look at the emissions of soot from ocean-going vessels. The study found that tugboats put out more soot for the amount of fuel used than other commercial vessels, and that large cargo ships emit more than twice as much soot as previously estimated. A new instrument developed by the researchers, called a photoacoustic spectrometer, enabled them to capture a wealth of ship data in open ocean waters, channels, and ports along the southeast United States and Texas during the summer of 2006 Texas Air Quality Study. They measured black carbon emitted by more than 100 ships, including tankers, cargo and container ships, large fishing boats, tug boats, and ferries, many of them in the Houston Ship Channel. Commercial shipping releases roughly 130,000 metric tons of soot per year, or 1.7% of the global total, much of it near highly populated coastlines, the researchers estimate. Global shipping is expected to grow 2 to 6% annually in the coming years, and may expand in climate-sensitive areas such as the Arctic. Soot is both a health hazard and a climate-warming agent.

Impacts of Global Transport of Pollutants on Air Quality.[12,13,14,15] Observations on the ground, by airplane, and by satellite of ozone and particulate matter have shown that their concentrations are influenced by intercontinental transport of pollutants throughout the Northern Hemisphere. International collaboration has resulted in new multi-model experiments that have begun to refine our understanding of the source-receptor relationships for these pollutants on intercontinental scales. Current estimates suggest that the contribution of intercontinental transport of air pollution into the United States can be of the same order of magnitude as the pollution reductions expected from recent national emission control regulations.

Quantifying Aerosol Emissions from Biomass Fires.[16,17,18] Insufficient data on aerosol emissions and impacts is one of the largest sources of error in modeling the impacts of atmospheric changes on climate. Recent laboratory and small-scale field studies are quantifying the energy release from burning of common wildland fuels and correlating it to measured fuel consumption and aerosol emissions. Fire radiative energy (FRE) measured with a thermal imaging system explained close to 90% of the variation in fuel consumption, and measured emission factors for aerosols and other components were similar to those that have been observed in field studies. A strong correlation was also observed between FRE and the level of particulate emissions. This research holds great promise for the potential to accurately estimate aerosol emissions from wildfires and other biomass fires using aerial and space-borne thermal imagers. Other work investigated biomass burning through a combination of modeling studies, incorporating both satellite- and ground-based monitoring data, and analysis of monitoring data

downwind from a prescribed burn. Prescribed burns and wildfires were shown to significantly affect regional air quality. An analysis of historic data indicates that in the coming decades climate change is likely to cause increases in wildfires and organic carbon particle concentrations, with implications for air quality.

Mechanisms in New Particle Growth: Role of Organics.[19] During the 2006 Megacity Initiative: Local and Global Research Observations (MILAGRO) field study, USGCRP scientists made measurements of the composition of ambient ultrafine (10–33 nm diameter) particles formed from nucleation in Tecamac, Mexico. They discovered that recently nucleated particles contained about eight times as many organics as sulfates. The measured organic species include nitrogen-containing organic compounds, organic acids, and hydroxy organic acids. Independent calculations show that sulfuric acid condensation could have accounted for only 10 ± 2% of the growth that was observed on this day, which is consistent with the composition measurements. Clearly, organic compounds play a dominant role in the high particle growth rates that were observed near Mexico City; these mechanisms may also contribute to similar high growth rates observed in other locations.

Atmospheric Constituents other than CO_2 and Implications for Earth's Energy Balance

New Technique for Tropospheric Ozone Column Calculations.[20] USGCRP scientists have developed a technique for deriving tropospheric ozone column abundances by combining the total column ozone products and the stratospheric profile abundances from instruments on the Aura satellite. This technique, which employs atmospheric transport back trajectories to link the Microwave Limb Sounder (MLS) and the Ozone Monitoring Instrument (OMI) observations spatially and temporally, provides the most precise technique to date for obtaining tropospheric ozone measurements from space. These early data sets resulted in the first global tropospheric maps that show streams of tropospheric ozone crossing the oceans. The USGCRP scientists validated this technique using ozonesonde data from the many international ozonesonde programs and found derived columns to be statistically equivalent to the tropospheric columns from the sondes. This technique appears to produce better results than similar past efforts of combining different data sets. In 2010, these data will be used to assess the anthropogenic and stratospheric contributionsto upper tropospheric ozone, a strong greenhouse gas.

Sea Salt Adds Pathway for Pollutants to Make Ozone.[21] Chemically active trace gases that contain the halogens chlorine, bromine, or iodine are important in the chemistry of the lower atmosphere, especially oxidant chemistry at mid-latitudes. However, the detailed chemical processes that convert and cycle halogens in the lower atmosphere are still quite uncertain. USGCRP scientists have made the first real-world observations of nitryl chloride ($ClNO_2$), a potentially important source of active halogens in the coastal troposphere that forms at night from the interaction of nitrogen oxide (NO_x) pollution and sea salt. The authors concluded that in addition to sea salt, many other particles containing chloride also lead to $ClNO_2$ production. The formation of $ClNO_2$ is significant because during the daytime, it breaks down and the products form ozone. The levels of $ClNO_2$ observed in this study are much greater than earlier estimates based on numerical models. The results indicated that the $ClNO_2$ chemistry could affect oxidant formation in areas where NO_x and sea-salt chloride sources exist. Just over half of the global population resides within 200 km of a coastline, where such processes could enhance the production of ozone. Climate-related effects could also occur through radiative forcing by ozone, as well as through the interaction of released halogens with sulfur chemistry in the marine atmosphere.

Research Advances Understanding of the Distribution, Seasonality, and Sources/Sinks of Atmospheric Carbonyl Sulfide.[22] Carbonyl sulfide (COS) is the most abundant sulfur-containing trace gas in the atmosphere, yet a coherent picture of its distribution and seasonal/interannual variability has been elusive. USGCRP researchers have remedied that situation by analyzing several years of data from a global ground- and aircraft-based air-monitoring network to identify the primary factors that underlie the atmospheric occurrence of COS. The results demonstrate that different processes in each hemisphere drive COS seasonal behavior. In the Northern Hemisphere, summer uptake by terrestrial vegetation plays a dominant role in COS abundance and was found to be about five times higher than estimates. The

oceans are the primary influence in the Southern Hemisphere. Biomass burning appears to have a smaller influence on seasonal COS behavior compared to the oceans and terrestrial vegetation. The vegetative uptake of COS parallels the uptake of CO_2 during photosynthesis and could be useful as an independent way of estimating gross carbon uptake by vegetation. The analyses suggest that COS sources have been underestimated significantly in present budget estimates for COS.

Differences in Atmospheric Processing of Sulfate and Water-Soluble Organics Affect Downwind Influence and Long-Range Transport Potential.[23,24] Increasing anthropogenic pollution and long-range transport are leading to hemispheric-scale changes in atmospheric composition. Understanding these changes requires knowledge of emission sources as well as the transformation and fate of those emissions during long-range transport. The Intercontinental Chemical Transport Experiment, Phase B (INTEX-B) made observations over the eastern, North Pacific and western United States during the spring of 2006 to examine the influence of transpacific transport of polluted air masses from Asia to North America. Segregating these observations by local (North American) versus transported (Asian) influence revealed a large difference in the relative amounts of sulfate and water-soluble organic carbon found in fine particulate matter. As compared to previous observations near sources along the Asian Pacific Rim and over North America, the transported air masses exhibited depletion of organic aerosol as compared to sulfate. These data suggest that aerosol formation from the oxidation of volatile organics proceeds more rapidly (<1 day) than does oxidation of sulfur

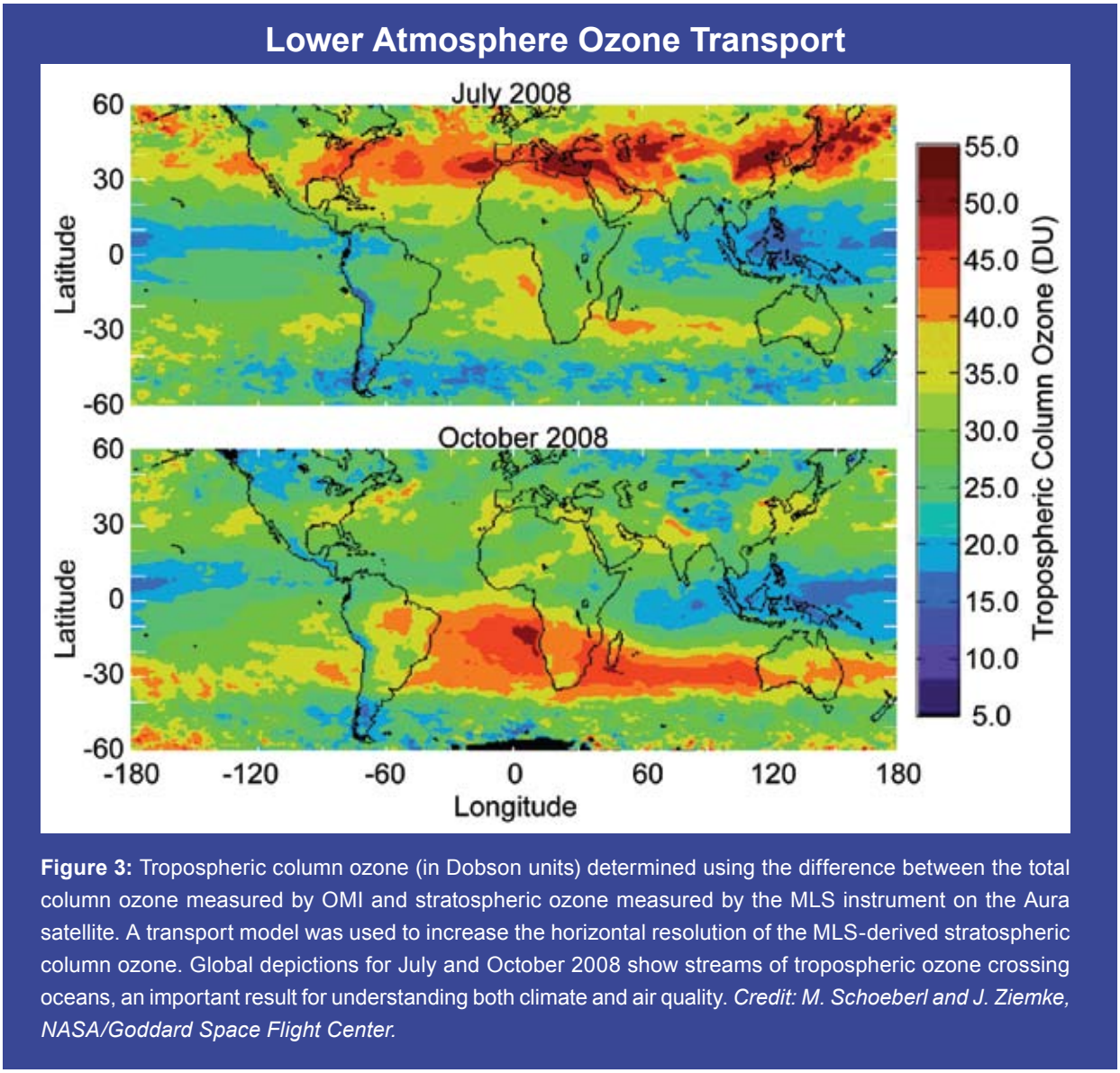

Figure 3: Tropospheric column ozone (in Dobson units) determined using the difference between the total column ozone measured by OMI and stratospheric ozone measured by the MLS instrument on the Aura satellite. A transport model was used to increase the horizontal resolution of the MLS-derived stratospheric column ozone. Global depictions for July and October 2008 show streams of tropospheric ozone crossing oceans, an important result for understanding both climate and air quality. *Credit: M. Schoeberl and J. Ziemke, NASA/Goddard Space Flight Center.*

dioxide. This rapid formation allows for the loss of most organic aerosol in precipitation associated with frontal lifting along the Asian Pacific Rim, which is the primary mechanism for long-range transport across the North Pacific. Additionally, it was shown that although secondary organic aerosol formation from pollution happens on the time scale of one day, the oxidation of organic aerosol continues at longer time scales in the atmosphere during transpacific transport. A significant fraction of sulfur dioxide is not washed out and continues to be oxidized to form sulfate aerosol during transport.

Use of Unmanned Aircraft for Stratospheric Measurements. USGCRP scientists make use of airborne measurements, both remote and in situ sensing, to further scientific understanding and to calibrate and validate satellite remote sensing of the Earth system. Agencies are increasingly incorporating unmanned aircraft systems (UASs) in their airborne research missions. The UAS platforms are expanding research horizons by enabling missions to be carried out in previously inaccessible regions, or under conditions considered too risky for manned aircraft. One such UAS, the Global Hawk developed for the Department of Defense, brings important new capabilities for scientific inquiry. For example, Global Hawk can remain airborne at cruise altitudes in the lower stratosphere for more than 30 hours, enabling extensive geographic coverage and/or continuous observation of diurnal cycles. USGCRP researchers will use Global Hawk to investigate the composition of the upper atmosphere and to aid in the calibration and validation of remote sensors on the Aura Earth Observing Satellite. In particular, in situ measurements of certain chemically and climatically important gas phase compounds and aerosols, as well as remote-sensing observations of the vertical profiles of aerosols, clouds, temperature, and pressure will be made. Another study conducted during August and September 2008, originating from Cheju, South Korea, made use of UASs developed by Advanced Ceramics Research Inc. to study pollution during the period when emissions were temporarily and drastically reduced for the 2008 Summer Olympics in China.

Synthesis and Assessment Products

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAPs most relevant to Atmospheric Composition and completed within the period of this report are as follows:

SAP 2.3: Atmospheric aerosol properties and climate impacts (2009)

SAP 2.4: Trends in emissions of ozone-depleting substances, ozone layer recovery, and implications for ultraviolet radiation exposure (2008)

SAP 3.2: Climate projections based on emissions scenarios for long-lived and short-lived radiatively active gases and aerosols (2008)

HIGHLIGHTS OF PLANS FOR FY 2010

The USGCRP will continue to gather and analyze information through measurement, modeling, and assessment studies to enhance understanding of atmospheric composition and of the processes affecting atmospheric chemistry. In FY 2010, the following research activities will be emphasized to meet the overall priority.

Continued Analysis of Data from International Polar Year (IPY) 2008 Campaigns. Several Federal agencies carried out major field campaigns in the Arctic during IPY 2008. Efforts in FY 2010 will focus on data analysis, publication of peer-reviewed papers, and communicating the results in other fora. The Arctic is a sensitive region that may be warming faster than the average across the globe.

This activity will address Questions 3.1, 3.3, and 3.5 of the 2003 Strategic Plan.

Analysis of Data from the 2008 VOCALS Campaign. NOAA, DOE, NSF, the Office of Naval Research (ONR), and international partners collaborated on the VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study) field program, carried out during October and November 2008 in the Southeast Pacific. The objectives were to better understand physical and chemical processes central to the climate system of this region. Efforts in FY 2010 will focus on analysis and modeling of results from VOCALS.

This activity will address Questions 3.1, 3.3, 4.1, and 8.1 of the 2003 Strategic Plan.

Investigation of the Relationship between Black Carbon (Soot) and Other Pollutants. The role of black carbon in climate is complex, involving direct and indirect

effects that have large uncertainties. USGCRP research will examine the relationships between black carbon and other pollutants, such as carbon monoxide, that could prove useful in estimating black carbon mass loadings from more widely available measurements.

This activity will address Questions 3.1 and 3.5 of the 2003 Strategic Plan.

Planning for NASA Decadal Survey Missions. USGCRP scientists have embarked on the early planning processes for several NASA Decadal Survey missions that will concentrate primarily on atmospheric composition. Three of the missions designated as "Tier 2" by the National Research Council panel that assembled the Decadal Survey will directly observe the atmosphere. The Aerosol and Cloud Experiment (ACE) is currently designed to have cloud radars, aerosol and cloud lidars, and aerosol polarimeters, along with an ocean color sensor. The Active Sensing of CO2 Emissions over Nights, Days, and Seasons (ASCENDS) is a laser-based satellite sensing system for CO2 that also calls for some passive remote sensing of carbon monoxide and potentially other molecules. The Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission contains multiple passive remote-sensing instruments to observe tropospheric composition at finer spatial and temporal scales than have ever been observed from space through observations from a geostationary orbit over the Western Hemisphere. This mission also calls for a very high-resolution coastal ocean imager to observe fine-scale ocean biogeochemical processes at high temporal resolution. All of these missions are conducting studies to refine the science questions in order to clearly define the types of observations that can and should be made to address the science needs. These studies are also intended to spell out the technology developments needed to get these mission concepts closer to full mission development. Potential launches for these missions fall in the 2016 to 2022 time frame.

This activity will address Questions 3.1 and 3.2 of the 2003 Strategic Plan.

Hemispheric Transport of Air Pollution. In fall 2009, the National Research Council of the National Academy of Sciences will complete an interagency-funded study of the significance of the international transport of air pollutants for air quality and climate change. At the international level, the United States will contribute to an assessment of intercontinental transport of air pollution produced under the auspices of the United Nations Economic Commission for Europe's Task Force on Hemispheric Transport of Air Pollution to be completed by June 2010.

These activities will address Questions 3.1 and 3.3 of the 2003 Strategic Plan.

Interactions between Climate Change and Air Quality. Understanding the combined effect of climate change and air quality is a key research question. Continuing work in FY 2010 will focus on 1) reducing the uncertainty for ground-level ozone; 2) assessing the impact of climate change on particulate matter; and 3) preliminary research to enable assessment of interactions with mercury. The FY 2010 work focuses on linked air quality-climate modeling systems, future emission projections, and communicating research results to air quality decisionmakers. In FY 2010 an intensive field study in California, CalNex, will provide an initial opportunity to characterize and quantify atmospheric processes and emissions that link these two issues with the latter FY 2010 focus areas.

This activity will address Questions 3.3 and 3.5 of the 2003 Strategic Plan.

Impacts of Aircraft Emissions on the Atmospheric Composition and Climate. USGCRP participating agencies will pursue solution-focused research that will directly support decisionmaking toward achieving the climate goals of the U.S. Next Generation Air Transportation System (NextGen). The effort will be guided by a report that clearly identifies key research gaps and priorities.[25] Some of the key high-priority research and impact assessment needs include (1) measurement and analysis of upper troposphere/lower stratosphere specific data for temperature, relative humidity, and ice supersaturation; (2) new observations of contrails and induced cirrus clouds and analysis of existing data in correlation with aviation activity; (3) development of subscale parameterization of physical processes for simulations of contrails and cirrus clouds; (4) research into the interplay of NOx and odd hydrogen particularly at high NOx levels within the upper troposphere/lower stratosphere region; (5) assessment of climate impacts under various aviation emission scenarios; and (6) development and evaluation of metrics that can account for wide spatial and temporal ranges of climate impacts related to aviation emissions.

This activity will address Questions 3.3 and 3.5 of the 2003 Strategic Plan.

CHAPTER REFERENCES AND ENDNOTES

[1] See the following websites for more information on these studies:

Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models, of climate, chemistry, aerosols, and Transport (POLARCAT) research activity: <www.polarcat.no>;

Aerosol, Radiation, and Cloud Processes affecting Arctic Climate study (ARCPAC): <www.esrl.noaa.gov/csd/arcpac/>;

International Chemistry Experiment in the Arctic Lower Troposphere (ICEALOT) campaign: <saga.pmel.noaa.gov/Field/icealot/>;

Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission: <www.nasa.gov/mission_pages/arctas/>; and

Indirect and Semi-Direct Aerosol Campaign (ISDAC): <acrf-campaign.arm.gov/isdac/>.

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2 CLIMATE VARIABILITY AND CHANGE

Strategic Research Questions

4.1 To what extent can uncertainties in model projections due to climate system feedbacks be reduced?

4.2 How can predictions of climate variability and projections of climate change be improved, and what are the limits of their predictability?

4.3 What is the likelihood of abrupt changes in the climate system such as the collapse of the ocean thermohaline circulation, inception of a decades-long mega-drought, or rapid melting of the major ice sheets?

4.4 How are extreme events, such as droughts, floods, wildfires, heat waves, and hurricanes, related to climate variability and change?

4.5 How can information on climate variability and change be most efficiently developed, integrated with non-climatic knowledge, and communicated in order to best serve societal needs?

See Chapter 4 of the *2003 Strategic Plan* for detailed discussion of these research questions.

To address fundamental goals described in the *2003 Strategic Plan*, climate variability and change (CVC) research focuses on improving descriptions and understanding of past and current climate and advancing national modeling capabilities to project future changes in climate and related Earth system components (land, oceans, cryosphere, and biosphere). Research under this element encompasses time scales ranging from short-term climate variations of a season or less to longer-term climate changes spanning decades to centuries. CVC places a high priority on improving understanding and predictions of phenomena that can cause large impacts on society, the economy, and the environment. Examples include understanding the relationships between climate variations and change and extreme events; predicting major climate variations like the El Niño-Southern Oscillation and their attendant impacts; projecting future changes on decadal to centennial time scales; and assessing the potential for accelerated or abrupt climate changes, for example, those related to changes in sea level, the ocean circulation, sea ice, or glaciers and ice sheets. Addressing such challenges requires integrated approaches to the observation, analysis, and modeling of interactions and feedbacks among different Earth system components.

Considerable advances are being made in this area through the development and planned application of Earth system models in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment. CVC is also emphasizing the development of new capabilities to integrate diverse observations within Earth system models to produce internally consistent maps of atmospheric, oceanic, land surface, and ice conditions. These "Earth system analyses" will extend the ability of scientists to understand and explain past and current climate conditions, and will provide decisionmakers with new tools to identify changes in the climate system and their attendant impacts over the entire planet. CVC also emphasizes focused research on climate processes to advance understanding of the causes of climate variations and change, assess climate feedbacks that influence climate sensitivity and responses, and improve models required for climate predictions and global and regional climate change projections.

Research within CVC focuses on two broad, critically important questions to society defined in the *2003 Strategic Plan*:

- How are climate variables that are important to human and natural systems affected by changes in the Earth system resulting from natural processes and human activities?
- How can emerging scientific findings on climate variability and change be further developed and communicated in order to better serve societal needs?

More specifically, CVC research addresses the five strategic research questions listed at the beginning of this chapter and described in the *2003 Strategic Plan*. Cooperative efforts involving USGCRP agencies have led to significant progress in addressing the strategic questions. The following section highlights some of the major scientific advances achieved during this past fiscal year.

HIGHLIGHTS OF RECENT RESEARCH

This year's highlights of CVC research emphasize advances in several areas. They range from studies providing a more fundamental understanding of past and present climate to research that has implications for issues such as water management and food production in Africa.

Extending Climate Records.[1,2] Proxy climate data (tree rings, ice cores, and other evidence) from the past 2,000 years are now being formally integrated with the past 150 years of instrumental climate data to produce an unprecedented view of climate change. A new reconstruction of surface global and hemispheric temperatures for the past 2,000 years, using a greatly expanded set of proxy data, was developed following recommendations from the National Research Council (NRC). Significantly, the study demonstrates that the current warmth of the Northern Hemisphere appears anomalous for at least the past 1,300 years, whether or not previously challenged tree ring data are used. The warming during the Medieval Warm Period is greater than hitherto reported, albeit still not reaching recent levels. To make the paleoclimate data and infrastructure used in IPCC Fourth Assessment Report (AR4) available, the full reconstruction data sets used in that assessment have now been centrally archived.[3]

Drought Causes and Predictability[4,5,6] An observational study examined regional differences in the characteristics of droughts and extended wet spells across the United States and Mexico. Wet or dry conditions that persist for more than one year occur mainly in the western United States and northwest Mexico, while in the eastern United States prolonged hydrological regimes usually last less than six months. The most persistent regimes are frequently associated with changes in Pacific Ocean sea surface temperatures (SSTs). To what extent, then, might long-duration droughts be predictable from foreknowledge of SSTs? This question is being addressed for the "Dust Bowl" drought that affected much of the United States in the 1930s. One modeling study found that advance knowledge of tropical SSTs would have allowed a high-confidence prediction of severe drought over portions of the United States in the 1930s, although compared to observations the model drought was centered too far south and did not show observed continental warming. A second study found that including dust effects associated with land degradation in addition to SST patterns led to a more intense and a slightly more spatially realistic drought. Research is continuing to further assess the roles of various factors in producing long-duration droughts such as occurred during the Dust Bowl years and the potential implications for predicting future droughts.

Identifying Causes of Climate Trends[7] Climate trends observed over the United States during the second half of the 20th century differ by season and region. To understand these differences, SST variations observed during the period were decomposed into three leading patterns (a global warming linear trend pattern, a Pacific decadal pattern, and an Atlantic multi-decadal pattern), which were then used, individually and in combination, to force atmospheric climate models. Results confirm that the global warming pattern is important for explaining the annual mean, area-average warming trend over the United States, but it contributes little to the seasonal or regional variations in the trends. Comparing the observed and simulated maps of U.S. seasonal temperature trends, it appears that the cooling trend over the central United States in summer and fall is due mostly to the Pacific decadal SST pattern. Another important factor during these two seasons is the Atlantic multi-decadal SST pattern.

The Flow of Energy Through the Climate System.[8,9,10] Updated estimates have now been produced for trends, variability, and mean amounts of the annual cycle of energy flowing through the climate system, and the energy storage, release, and transport in the atmosphere, ocean, and land surface. The estimates were obtained from recent observations using the latest data sets. The results indicate that the global energy budget can now be estimated reasonably well, with the largest continuing source of uncertainty being the ocean heat budget south of about 35°S. The current imbalance in radiation at the top of the atmosphere owing to human-induced increases in greenhouse gases means that the atmosphere, land, and ocean are warming up, and ice is melting, leading to a rise in sea level. A holistic integrated approach that brings all information to bear provides constraints on what is happening and where the main weaknesses are in the current

Influence of Sea Surface Temperatures on Continental U.S. Temperatures

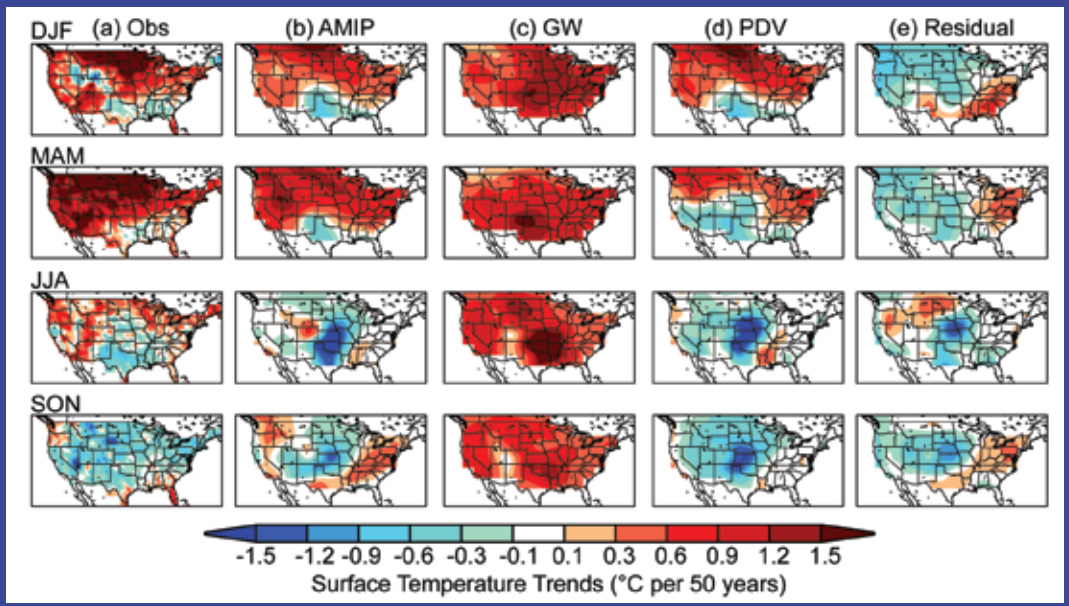

Figure 4: Observed seasonal trends in surface temperature (°C per 50 years) from 1950 to 2000 are displayed in column (a) for the 3-month seasons DJF, MAM, JJA, and SON. Column (b) shows comparable results from atmospheric model simulations driven by SST variations observed for the period; the correspondence with column (a) demonstrates the ability of the simulations to reproduce the main observed features. Columns (c) through (e) decompose the total modeled temperature responses in column (b) into components associated with each of the three leading SST patterns: (c) the global warming pattern, (d) the Pacific decadal SST pattern, and (e) the residual pattern, a manifestation of the Atlantic multi-decadal SST pattern. *Credit: H. Wang and S. Schubert, NASA/ Goddard Space Flight Center (adapted from the* **Journal of Climate** *with permission from the American Meteorological Society).*

observing system. These analyses also provide insights into both top-of-atmosphere and surface energy balances and model problems. For instance, the results indicate that climate models typically simulate too much downward longwave radiation, which is compensated by too much evaporation and precipitation.

Hurricanes and Climate Change.[11,12,13,14,15] The link between hurricanes and climate change continues to be actively investigated. Previous studies have found that variations in tropical cyclone activity are linked to changes in SSTs in the North Atlantic and western North Pacific tropical cyclone development regions. A recent study used a suite of climate models to demonstrate that a trend toward increasing SSTs in these regions is not consistent with either internal climate variability or a response to volcanic aerosols and solar irradiance changes, but is attributable to human influences. There is compelling evidence that increasing Atlantic hurricane activity since the 1970s has occurred with warming ocean conditions, but research indicates that the relationship between increasing SSTs and hurricane frequency is not simple. One study finds that effects of wind shear are more likely to inhibit initial tropical cyclone development when SSTs are warmer. Another study applied an ensemble of climate models to assess effects of climate changes on hurricane activity near the end of this century. That study finds that, despite warming ocean conditions, Atlantic hurricane and tropical storm frequencies are projected to decrease due to changes in tropical wind shear. However, near-storm rainfall rates do increase substantially due to atmospheric moisture increases. Another study applied a new technique for deriving hurricane climatologies to downscale projections from IPCC AR4 simulations. That work suggests that global warming should reduce the global frequency of hurricanes, although intensities may increase in some locations. Other recent research indicates the importance of secular changes in wind shear over the Atlantic main development region on the frequency of U.S. land falling storms. The studies together suggest the fundamental importance of projecting changes in tropical wind shear to anticipating future changes in hurricane activity.

Identifying Causes for 2007 Minimum Arctic Sea Ice Extent.[16,17,18,19] Satellite observations have shown a marked trend toward decreasing Arctic sea ice extent together with significant year-to-year variability over the period from 1979 to the present. Within this period, the decline in sea ice extent in 2007 was extraordinary, with the 2007 minimum areal extent falling 22% below the previous record low set in 2005. USGCRP research is focusing on the factors that contributed to this extraordinarily rapid sea ice loss. One study identified reduced cloudiness and enhanced downwelling radiation as key factors in the 2007 ice loss. The cloudiness variations were not unprecedented, but long-term warming has led to thinning of the sea ice, making it more

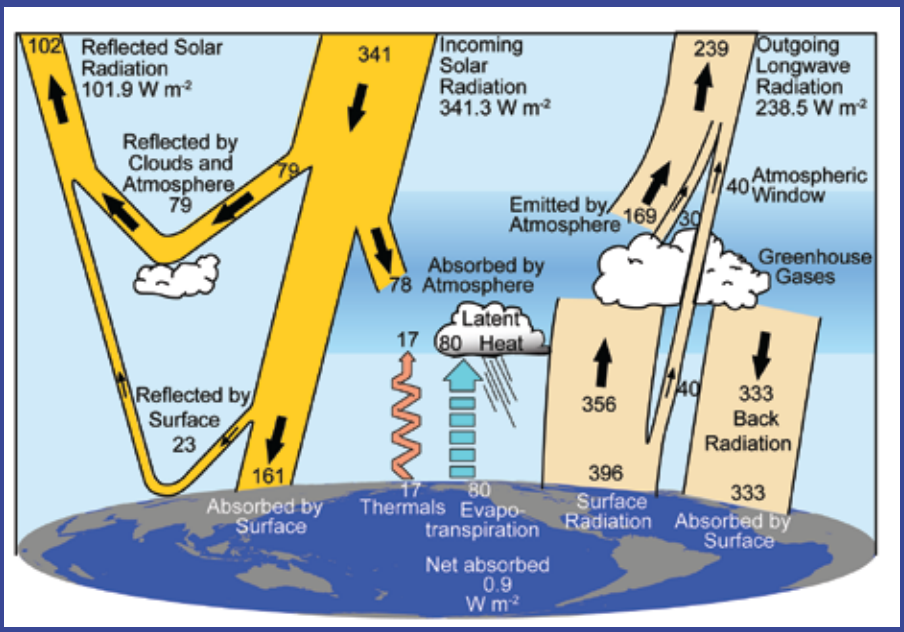

Figure 5: Estimated global annual mean energy flows for the 2000 to 2004 time frame. Notice the current imbalance between the annual average solar energy absorbed by the Earth system versus the outgoing longwave energy. *Credit: K.E. Trenberth, NCAR (reproduced from the* **Bulletin of the American Meteorological Society** *with permission from the American Meteorological Society).*

vulnerable to rapid losses. The reduced cloudiness and unusually warm conditions in 2007 were related to an exceptionally strong phase of one of the leading modes of natural climate variability, the Pacific-North American pattern. Another potential factor is ocean currents that have reduced sea ice in the marginal seas north of eastern Siberia and Alaska. The results of these studies indicate that long-term warming in the region is leading to decreases in sea ice thickness, and that when sea ice is thin, naturally occurring climate variations that affect both the atmosphere and oceans can lead to dramatic variations in sea ice extent.

Attribution of Observed Surface Humidity Changes.[20] Water vapor is the most important contributor to the natural greenhouse effect. The amount of water vapor in the atmosphere is expected to increase under conditions of greenhouse-gas induced warming, leading to a significant positive feedback to anthropogenic climate change. A recent study used a new data set of surface humidity observations together with output from a coupled climate model to detect a significant anthropogenic influence in observations of surface humidity. Specific humidity was found to have increased in response to rising temperatures, with relative humidity remaining approximately constant. These changes may have important implications, because atmospheric humidity is a key variable in determining the geographical distribution and maximum intensity of precipitation and the potential maximum intensity of tropical cyclones, and increases in humidity will lead to an increase in human heat stress.

Improving Model Predictions and Projections of El Niño.[21,22] State-of-the-art coupled ocean-atmosphere model predictions of the El Niño-Southern Oscillation (ENSO) typically suffer from a precipitous drop in forecast skill during boreal (Northern Hemisphere) spring. It remains uncertain whether this "spring barrier" is due to a fundamental property of the coupled ocean-atmosphere system or to errors in the coupled models. Recent work shows that in the case of one operational model, the spring barrier is due to model error, particularly in terms of how the model atmosphere responds to SST anomalies. This result offers hope for improving forecast skill during the boreal spring. Studies are also underway to understand the causes for differences among models in their simulations of ENSO and to develop metrics to compare different models and improve their performance.

The Influence of Winter Snowpack on Climate Models[23] Recent work has uncovered a connection between the spring melting of the North American snowpack in climate models and their simulation of the degree of climate change in the central United States. Snow-albedo feedback refers to a process where warming temperatures reduce snow cover, the exposed Earth then absorbs more radiation from the sun, leading to further atmospheric warming. The study finds that climate models that include a stronger level of snow-albedo feedback end up projecting warmer and dryer conditions, even into the summer, due to the lack of water stored as soil moisture. The study concludes that by incorporating realistic values of snow-albedo feedback, confidence in simulations of North American summer climate will be greatly increased.

Antarctic Ozone Hole Recovery May Keep Southern Hemisphere Cooler.[24] Climate models show that the increase in greenhouse gases and the stratospheric ozone hole have together affected the location of the Southern Hemisphere jet stream. The position of the jet stream, in turn, has direct implications for surface temperatures, sea ice, and many other factors related to Southern Hemisphere climate. Projecting forward, about half of the current IPCC models do not include the recovery of ozone expected from restrictions set forth in the Montreal Protocol. In a recent study, a model that includes a full representation of the stratosphere shows that the increase in ozone may reverse the southward trend of the jet stream, which could ease the effects of climate change in the Southern Hemisphere.

Additional highlights of recent research on climate variability and change have been included in the analysis of progress toward goals section in the introductory chapter of this report.

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAPs most relevant to Climate Variability and Change and completed during the period of this report are as follows:

SAP 1.2: Past climate variability and change in the Arctic and at high latitudes (2009)

SAP 1.3: Reanalysis of historical climate data for key atmospheric features: Implications for attribution of causes of observed change (2008)

SAP 3.1: Climate models: An assessment of strengths and limitations (2008)

SAP 3.2: Climate projections based on emissions scenarios for long-lived and short-lived radiatively active gases and aerosols (2008)

HIGHLIGHTS OF PLANS FOR FY 2010

Developing a National Capacity for Integrated Earth System Analysis. The USGCRP continues to place high priority on developing a national capacity for integrated Earth system analysis that will enable scientists to better assess interactions among Earth system components that can produce rapid or unexpected climate changes, as well as advance understanding and predictions of the coupled climate system. Achieving this capability requires parallel advances in Earth system modeling and the ability to assimilate increasingly diverse observations into models. In FY 2010, an analysis will be conducted emphasizing the hydrological cycle and evaluating the impacts of satellite data on the representation of climate variability and trends. The reanalysis data set used for this purpose will also help support research and modeling capabilities required to improve seasonal-to-interannual climate forecasts.

This activity will address Goals 1 and 3 and Questions 4.2, 4.4, and 4.5 of the 2003 Strategic Plan.

Abrupt Climate Change: Observations and Modeling. The ability of climate models to accurately reproduce past climate changes is an important measure of the confidence that can be placed in these models' projections for the future. USGCRP agencies plan to initiate an activity in FY 2010 to simulate time periods of particularly rapid change during the current interglacial and past glacial periods. Assessing the potential for future abrupt climate change based on projections from coupled climate models will also be continued. Ongoing efforts by the USGCRP to archive past climate data from ice cores, sediments, and other sources will provide a benchmark for the climate models.

This activity will address Goals 1 and 3 and Questions 4.1, 4.2, 4.4, and 4.5 of the 2003 Strategic Plan.

Arctic Climate History. A project is planned to investigate the paleoclimatic history of the Arctic Ocean and surrounding marine regions with emphasis given to the impact of climate change on the natural resources of coastal Alaska, the Greenland-Norwegian-Icelandic Seas, and the Nares Straits. The focus will be on using sediment- and ice-core records collected from field campaigns over the last two decades to examine several topics including epochs of global warmth, sea ice history, links between the North Atlantic and global climate, and climate impacts on marine ecosystems.

This activity will address Goal 1 and Questions 4.3 and 4.5 of the 2003 Strategic Plan.

Atlas of Glaciers of the World.[25] Most mountain glaciers and polar ice caps worldwide have been retreating since the late 1800s, and global sea level has risen about 15 cm since then. Glaciers vary in size in response to changes in global and regional climates. A thorough global baseline study of the areal extent of existing glaciers is required before scientists can assess the magnitude of glacier change that is forecast to occur worldwide during the 21st century. Satellite images are being used to inventory glaciers now and to monitor changes in their areal extent over time. Portions of this atlas have already been completed, and work will continue in FY 2010 to complete volumes on Asia, Iceland, and permafrost and periglacial environments.

This activity will address Goal 1 and Questions 4.3 and 4.5 of the 2003 Strategic Plan.

Year of Tropical Convection (YOTC). The realistic representation of tropical convection in global models is a long-standing challenge for both numerical weather forecasts and climate prediction. The Year of Tropical Convection (YOTC) is a multi-agency, World Climate Research Programme (WCRP) and World Weather Research Programme / The Observing System Research and Predictability EXperiment (WWRP/THORPEX) joint initiative to address this challenge. YOTC began in FY 2008 as a year of coordinated observing, modeling, and forecasting with a focus on organized tropical convection, its prediction, and predictability. In FY 2008 and FY 2009, special data-model analyses at a resolution of approximately 20 km and daily 10-day forecasts are being produced, archived, and made available to the research and operational communities, along with analysis and visualization tools. During FY 2010 this vast data-model information resource will provide data for individual and coordinated research projects on the predictability and prediction of high impact weather and climate phenomena that are strongly influenced by tropical convection, including convectively coupled waves and the Madden-Julian Oscillation, active/break periods of the summer monsoons, easterly waves and tropical cyclones, the diurnal cycle, and extratropical weather influenced by tropical convection.

This activity will address Goal 1 and Questions 4.1 and 4.2 of the 2003 Strategic Plan.

Exploiting VOCALS-REx datasets. The Variability of the American Monsoon Systems (VAMOS) Ocean-Cloud-Atmosphere-Land Study—Regional Experiment (VOCALS-REx) is an international, multi-agency field observational experiment deployed in FY 2009 and designed to understand better the physical and chemical processes central to the climate system of the Southeast Pacific. In FY 2010, VOCALS-REx observations will provide the basis for modeling and analysis projects to study interactions among clouds, aerosols, marine boundary layer processes, upper ocean dynamics and thermodynamics, coastal currents and upwelling, large-scale subsidence, and regional diurnal circulations. These studies will include the development of a coupled regional Earth system model that includes oceanic and atmospheric dynamics, cloud and aerosol processes, atmospheric chemistry, and the biogeochemistry of the upper ocean. VOCALS research is driven by the need for improved global model simulations of the stratocumulus regions off the west coasts of North and South America and Africa. The persistent cloud shields in these regions are of great importance to the energy budget of the entire planet.

This activity will address Goal 1 and Questions 3.1, 3.3, 4.1, and 8.1 of the 2003 Strategic Plan.

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3 GLOBAL WATER CYCLE

Strategic Research Questions

5.1 What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

5.2 How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

5.3 What are the key uncertainties in seasonal to inter-annual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

5.4 What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

5.5 How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

See Chapter 5 of the *2003 Strategic Plan* for detailed discussion of these research questions.

The global water cycle plays a critical role in the functioning of the Earth system. Through complex interactions, the global water cycle integrates the physical, chemical, and biological processes that sustain ecosystems and influence climate and related global change. Inadequate understanding of the water cycle is one of the key sources of uncertainty in climate change prediction and projections. Clouds, precipitation, and water vapor play important roles in feedbacks that are not well represented in many climate models. Several aspects of atmosphere-land surface interactions, including biological and terrestrial hydrological processes, are still inadequately understood, leading to deficiencies in their parameterization in simulation and prediction models that are used for natural hazard forecasting, water resources management, and other decisions of societal relevance. The processes described above alter surface and atmospheric heating and cooling rates, leading to adjustments in atmospheric circulation and precipitation and evaporation patterns. Improved understanding of these processes is essential to developing options for responding to the consequences of water cycle variability and change.

Decisionmakers, including infrastructure planners, natural resource managers, water resources managers, as well as policymakers and other stakeholders, are addressing climate change issues while identifying the mitigation and adaptation measures that can be implemented to cope with long-term changes in the availability, quality, flow, and seasonal timing of surface and subsurface water. State-of-the-art Earth system models that are used to make projections about future hydrologic conditions often do not provide the adequate type and scale of hydrologic information needed for decisionmaking pertaining to water quantity and quality. Major challenges still remain in advancing from global scenarios to regional specificity. There are several critical scientific issues that need to be resolved before regional assessments can be made with the accuracy called for by the decisionmaking process, whether at the local, State, or Federal level.

Through improved understanding, observations, monitoring, and modeling, the water cycle program is structured to pursue research on key science issues that provide the basis for a series of applications of significant benefit to a broad range of end communities. Priority science research goals include:

- Develop strategic frameworks to integrate fundamental global water cycle and terrestrial hydrologic research that addresses societal needs in a changing climate, including the development and implementation of informed adaptation and mitigation strategies, assessments, and other decision support tools and processes.
- Develop and enhance observing and monitoring networks that provide the necessary data for hydrologic cycle research and end use operations, and provide critical links to other ecosystem services.
- Identify deficiencies in cloud formulations and cloud feedback representations in climate models, and improve cloud process representations. Quantify the magnitude of aerosol indirect effects on clouds and their effects on precipitation and the broader hydrologic cycle.
- Improve observations and modeling of processes and feedbacks including snow and ice packs freeze/thaw, soil moisture, and groundwater interactions.
- Link global climate models to regional- and/or local-scale hydrologic models, including the investigation of two-way interactions and feedback issues.
- Provide improved simulation and prediction of hydrologic parameters and conditions leading to extreme events, such as floods and prolonged droughts, in the context of changing intensity and frequency of such events.

As in previous years, the priorities in FY 2010 include the planning and implementation of integrated projects to accomplish the 2003 Strategic Plan goals for water cycle research, as well as newly identified research needs. As part of this process, the Federal agencies involved in the Water Cycle research element are defining a program of activities that are envisioned to lead to essential, interdisciplinary breakthroughs in water cycle science. Strategies for implementation include assembling long-term data sets of water cycle variables, implementing new tools and techniques, reanalysis of existing records, assimilating observations and model output, and establishing a network of observations with new capabilities for collecting and integrating data for interdisciplinary research. Collaboration with other program elements and end users will be critical in ensuring success. In addition to addressing goals, these ongoing and planned observations and research will contribute to the objectives of a broad array of national and international programs.

HIGHLIGHTS OF RECENT RESEARCH

Understanding and Predicting Drought Conditions

Reconstructing 20th-Century Droughts.[1,2] Retrospective simulations of near-surface soil moisture using land surface/hydrological models allow the study of drought events in the United States during the course of the 20th century. Simulations from an ensemble of six land surface/hydrological models suggest that models reconstruct the known severe continental U.S. drought events during the last century with plausible spatial extents and severities, although with substantial among-model disparities particularly for the western United States. Most models show that near-surface soil moisture-holding capacity is greater over the western United States than over the eastern part. Global and regional trends in drought for 1950 to 2000 were derived using a soil moisture-based drought index over global

terrestrial areas from a land surface/hydrologic simulation. There was a small overall wetting trend in global soil moisture that was forced by increasing precipitation, which was also weighted by positive soil moisture trends over the Western Hemisphere, especially in North America. Over the Americas, the spatial extents of areas affected by drought were shrinking. Long-term trends indicated considerable interannual and decadal variations in soil moisture and drought characteristics for most regions. Although there was an overall wetting trend globally, a drying trend since the 1970s occurred in many regions, especially in high northern latitudes. Significant drying over West Africa also stands out. This was shown to be caused, in part, by concurrent increasing temperatures. Although drought is driven primarily by variability in precipitation, the projected continuation of temperature increases during the 21st century indicates the potential for enhanced drought occurrence.

Improved Drought Monitoring Using Thermal Remote Sensing from Geostationary Satellites.[3] USGCRP scientists have successfully applied the Atmosphere-Land Exchange Inversion model to estimate the magnitude of vegetation water stress based on thermal infrared observations from geostationary satellites. The system is currently running quasi-operationally over the contiguous United States and will be expanded to include Europe, South America, North Africa, and the Middle East by 2010. The use of thermal infrared imagery provides a more direct and robust estimation of drought extent and magnitude than existing techniques derived from water balance modeling.

Cloud Water and Energy

Combined Cloud and Radiation Data for Climate Modelers.[4] Our ability to predict climate change continues to be hampered by uncertainties in cloud energy and hydrological processes. According to the most recent assessment by the Intergovernmental Panel on Climate Change (IPCC), the largest contributor to the range in sensitivity of climate models to the effects of greenhouse gases is in their treatment of the absorption and reflection of radiation by clouds. The development of a network of heavily instrumented ground-based observation stations in key climate regimes has given USGCRP scientists the ability to continuously measure cloud properties and their effect on the surface radiation

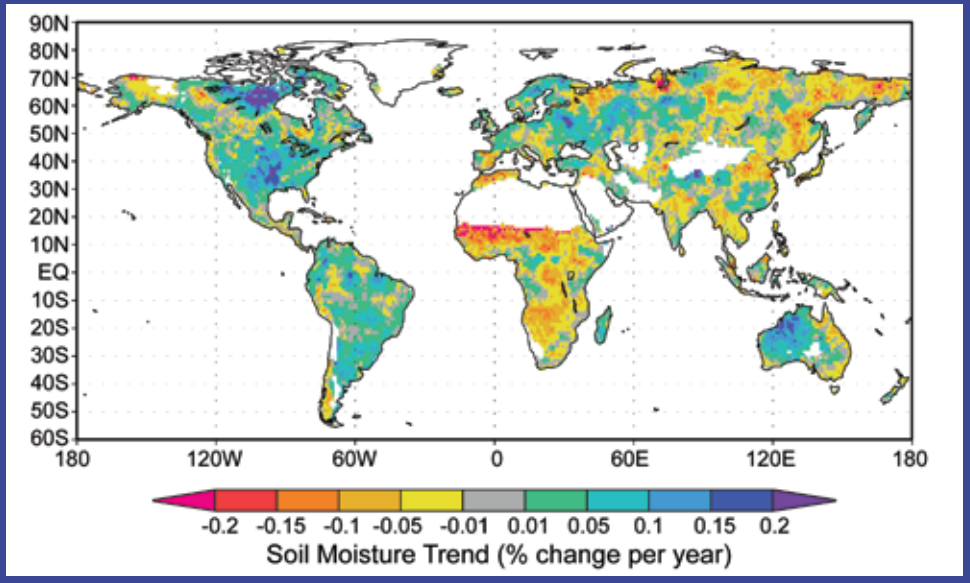

Figure 6: Global distribution of linear trends in annual mean volumetric soil moisture (percent change per year), 1950 to 2000. Regions with mean annual precipitation of less than 0.5 mm per day have been masked out. *Credit: J. Sheffield and E.F. Wood, Princeton University (adapted from the* **Journal of Climate** *with permission from the American Meteorological Society).*

balance. Using these detailed observations to improve climate models has resulted in a new data product, the "Cloud Modeling Best Estimate" (CMBE), which combines seven key cloud measurements and four components of surface radiative flux. A data set consisting of hourly averages of these quantities has been assembled for multiple years. Developed for use in modeling applications, the CMBE data draws on multiple instruments to produce the best estimate of cloud properties and surface fluxes at any given time. The CMBE combines critical atmospheric measurements into an efficient, comprehensive package for climate scientists to study the complex interactions between clouds and radiation.

Improvement of Cloud Parameterization in Global Climate Model.[5] Clouds play an important role in the Earth's radiation budget. In particular, clouds associated

Clouds in Earth's Energy Budget

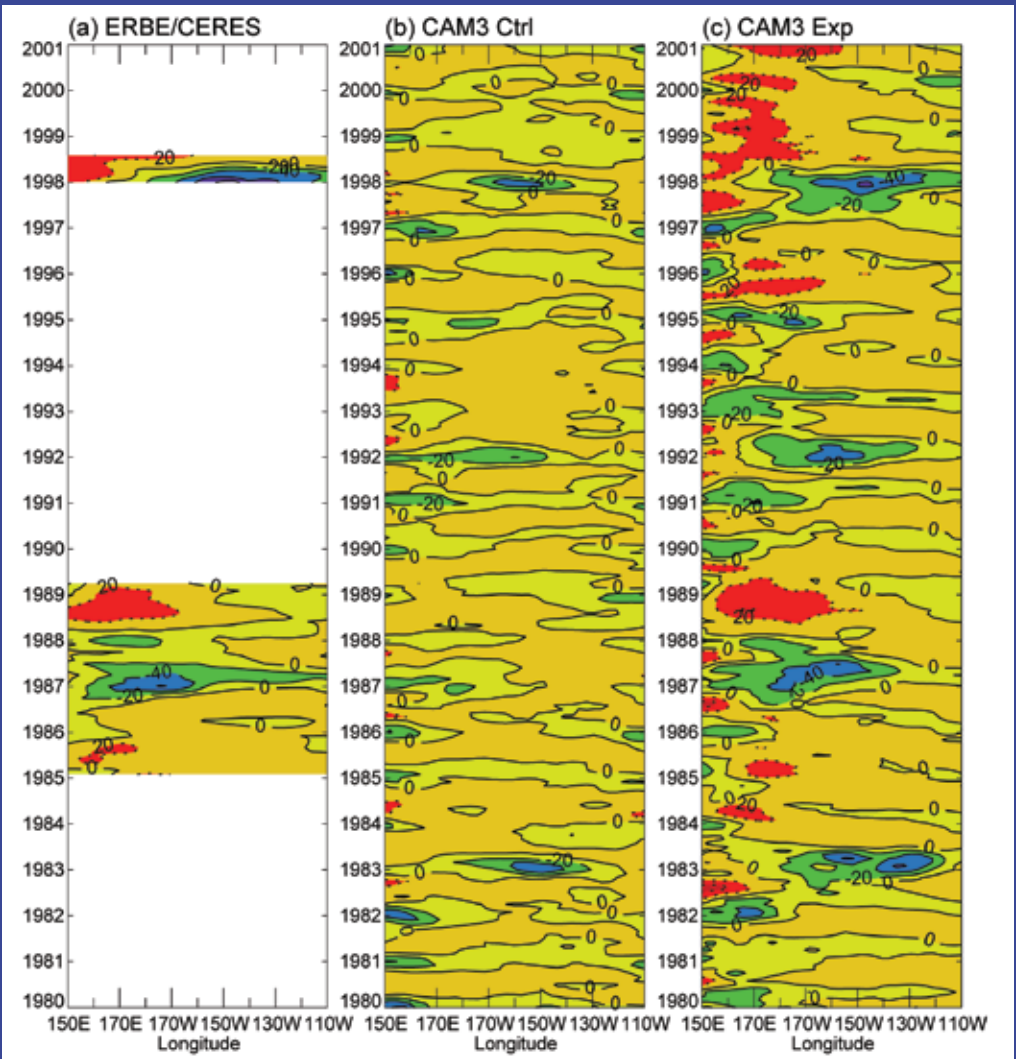

Figure 7: Shortwave cloud forcing (SWCF) anomalies from Earth Radiation Budget Experiment (ERBE) and Clouds and Earth's Radiant Energy System (CERES) observations and CAM3 simulations (Ctrl is the standard model; Exp includes the improved convection scheme). The anomalies are obtained by subtracting the mean SWCF from the observed or computed SWCF at each longitude over the period of interest, which is from Feb 1985 to Apr 1989 for ERBE and from Jan 1980 to Dec 2000 for CAM3. Contour intervals are 20 W m^{-2} with dotted lines for positive values. *Credit: G. Li Nanjing, University of Information Science and Technology, and G. J. Zhang, Scripps Institution of Oceanography (reproduced from* **Journal of Geophysical Research** *with permission from the American Geophysical Union).*

with El Niño contribute to interannual climate variability. Thus, it is critically important that global climate models simulate the radiative response to El Niño well in order for them to be useful for climate variability studies and future climate prediction. In this regard, at coarse resolution, the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) shortwave cloud radiative-forcing response to the El Niño-Southern Oscillation (ENSO) is known to be too weak compared to observations. It is natural to expect that the simulated El Niño may be sensitive to changes in the cloud parameterization scheme in the models. In an attempt to improve the shortwave cloud-forcing response to ENSO in CAM3, updated versions of cloud parameterizations were tested. The new cloud parameterizations were based on in situ and remote observations of convective clouds. The simulation period used (22 years) covers several El Niño and La Niña events, including the strong El Niño of 1997/1998. The CAM3, with the original cloud parameterization, did not reproduce observed shortwave cloud-forcing anomalies during these and other El Niño periods, instead producing anomalies with the wrong sign in the eastern Pacific. The newly developed cloud parameterization reproduced the observed shortwave cloud-forcing response well in the western and central equatorial Pacific. The model calculations with the revised cloud parameterization also simulate more accurately the observed relationship between shortwave cloud forcing and sea surface temperature than the standard CAM3.

Precipitation, Water Supply, and Soil Moisture

Atmospheric Warming and the Amplification of Precipitation Extreme Events.[6] Predicting and adapting to changes in the global water cycle expected to result from global warming presents one of the greatest challenges to humanity. Tropical precipitation projections through this century anticipate increases in moist, equatorial regions and indications of drying over the already-arid subtropics, changes consistent with theoretical considerations. Low-level atmospheric moisture increases with temperature at about 7% per °C, as expected from the relationship describing the change of phase of water (Clausius-Clapeyron equation), fueling comparable rises in heavy precipitation events, which are driven by moisture convergence. In this study, satellite observations were used together with model simulations to examine the response of tropical precipitation events to naturally driven changes in surface temperature and atmospheric moisture content. Observations revealed a distinct link between rainfall extremes and temperature, with heavy rain events increasing during warm periods and decreasing during cold periods. Furthermore, the observed amplification of rainfall extremes was found to be larger than that predicted by models, implying that projections of future changes in rainfall extremes in response to anthropogenic global warming may be underestimated.

Analysis of Tropical Rainfall Measuring Mission (TRMM)-Based Satellite Precipitation Products for Land Data Assimilation Applications.[7] The spatial and temporal structure of precipitation strongly influences land surface hydrological fluxes and states. Accurate measurements of precipitation at fine spatial and temporal scales have been shown to improve our ability to simulate land surface hydrological processes and states, such as floods and droughts. In this study, two TRMM-based precipitation products were assessed for hydrological land data assimilation applications. The two products, the gauge-corrected TRMM product, and the satellite-only product, were evaluated against ground-based rain gauge-only and gauge-corrected Doppler radar measurements. The analysis was performed at multiple time scales, ranging from annual to diurnal, for the period March 2003 through February 2006. The analysis showed that at an annual or seasonal time scale, the gauge-corrected TRMM product has much lower biases and root mean square (RMS) errors than the satellite-only product. The satellite-only product shows seasonally dependent biases, with overestimation in summer and underestimation in winter. This leads to a 50% higher RMS error in the satellite-only area-averaged daily precipitation than the gauge-corrected TRMM product. At shorter time scales (5 days or less), the satellite-only product has slightly less uncertainty, and about a 10 to 20% higher probability of detection of rain events than the gauge-corrected TRMM product. In addition, both of the satellite estimates detect more high-intensity events, causing a remarkable shift in the precipitation spectrum relative to surface-based products. Summer diurnal cycles in the United States are well captured by both products, although the 8-km horizontal resolution satellite-only product seems to capture more diurnal features

than the 0.25-degree (28 km) satellite-only or gauge-corrected TRMM products. The satellite-only product tends to overestimate the amplitude of the diurnal cycles, particularly in the central United States.

Climate Change Impacts on Water Supply.[8,9,10] Water managers throughout the Nation, especially in the southwest, have raised questions about the long-term sustainability of water supply in the region due to multiple stressors, such as the increased demand for water, recent multi-year drought, and projections of future global warming. In a recent study by the USGS Water Resources National Research Program, the potential effects of atmospheric warming on yearly streamflow were evaluated using a water balance model within the context of long-term climate variability determined by using tree ring data. The results indicate that if warming continues but is not accompanied by increased precipitation, there is an increased probability that streamflow in the Colorado River Basin will not meet the allocation requirements of the Colorado River Compact during multi-year droughts.

Development of a New Method to Evaluate Land Surface and Hydrologic Models.[11,12] The problems of identifying the most appropriate model structure for a given problem and quantifying the uncertainty in model structure remain outstanding research challenges for the discipline of land surface modeling and hydrology. The Framework for Understanding Structural Errors (FUSE) is a new methodology to diagnose differences in hydrological model structures. FUSE was used to construct 79 unique model structures by combining components of four existing hydrological models. These new model structures were used to simulate streamflow in two of the basins used in the Model Parameter Estimation Experiment (MOPEX): the Guadalupe River (Texas) and the French Broad River (North Carolina). Comparisons were made between the new FUSE model streamflow simulations and those simulations produced by MOPEX. The FUSE model simulations were at least as good as the simulations produced by the models that participated in MOPEX. The initial application of the FUSE method suggests that the choice of model structure is just as important as the choice of model parameters. Further work is needed to evaluate model simulations using multiple criteria to diagnose the relative importance of model structural differences in various climate regimes and to assess the amount of independent information in each of the models.

Effects of Complex Terrain on Surface Soil Moisture Patterns. Major uncertainties in hydrologic modeling stem from difficulties the climate models have in providing reliable information on hydrologic forcing by incoming precipitation and radiation. Researchers have developed an ensemble method for generating atmospheric forcing fields for assessing the uncertainty in simulated hydrologic response. These studies showed how static surface parameters such as topography impact patterns of hydrologic uncertainty. The information gained regarding the signature of topography seen in patterns of soil moisture provides valuable insights that climate modelers can use to improve results at model locations where rough or complex topography presents a major modeling challenge.

Network of Experimental Watersheds, Forests, and Ranges for Analysis and Observation of Climate Change and its Effects.[13,14] Interactions between climate change and watersheds are characterized by feedbacks, gradual trends, and extreme events that are best investigated with long-term experimental studies of hydrological processes and biological communities. This review identified 81 USDA experimental watersheds, forests, and ranges with data records of more than 20 years measuring important ecosystem dynamics such as variations in vegetation, precipitation, climate, runoff, water quality, and soil moisture. Through a series of examples, it showed how USDA long-term data have been used to understand key eco-hydrological issues, including (1) time lag between cause and effects, (2) critical thresholds and cyclic trends, (3) context of rare and extreme events and (4) mechanistic feedbacks for simulation modeling. New analyses of network-wide, long-term data from USDA experimental sites

were used to illustrate the potential for multi-year, multi-site climate and eco-hydrological research. Three areas of investigation were identified to best exploit the unique spatial distribution and long-term data of USDA experimental sites: convergence, cumulative synthesis, and autocorrelation. This review underscored the need for continuous, interdisciplinary data records spanning more than 20 years across a wide range of ecosystems within and outside the conterminous United States to address climate and eco-hydrology. USDA research plans include new long-term data collection efforts and adapting existing long-term data collection networks and natural observatories to include new and evolving climate change science issues.

Separating the Effects of Albedo from Eco-Physiological Changes on Surface Temperature.[15] In the southeastern United States, the conversion of abandoned agricultural land to forested ecosystems via both ecological succession and plantation forestry has been a dominant feature of land use change since post-Civil War reconstruction and the 1950s, respectively. Over the next 40 years, the area of land "populated" by pine plantations within the southeastern United States is projected to nearly double given the expected economic demand for forestry products, while agricultural acreage is expected to decline by one-third and upland hardwood forested area by a lesser extent. Such conversions would be expected to significantly alter the air and surface temperatures due to changes in the surface reflectance of sunlight (albedo) accompanying the vegetative changes. While incident sunlight is high in the Southeast compared to other forested regions within the United States, albedo is not the only factor affecting temperature. Changes in atmosphere-ecosystem energy exchange (evapotranspiration) and canopy height (a surrogate for roughness effects) affect temperature through evaporative cooling. To test the relative importance of these competing factors, researchers conducted a field experiment and showed that conversion of abandoned agricultural sites to pine plantations and hardwood forests under similar climatic and soil conditions results in surface cooling trends, that is, increased evaporative cooling and roughness effects counteract the warming due to albedo changes.

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAPs most relevant

to the Global Water Cycle and completed during the period of this report are as follows:

SAP 1.2: Past climate variability and change in the Arctic and at high latitudes (2009)

SAP 4.1: Coastal sensitivity to sea-level rise: A focus on the mid-Atlantic region (2009)

SAP 4.3: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States (2008)

HIGHLIGHTS OF PLANS FOR FY 2010:

In FY 2010, continuing U.S. and global observations, field campaigns, and experiments; improvements to data integration and analysis systems; diagnostic and prediction model development; and applications for decision support systems will be priorities under the USGCRP Water Cycle Program. A fundamental objective of the program is to ensure that observational capability is enhanced and improved, and that the data assimilation and modeling and prediction systems are more reliable. Several promising results from the past years of research will be further explored with an aim to convert this research knowledge to operational applications that provide societal benefit. A cohesive research strategy will be implemented to improve the deficiencies we see in understanding of the global water cycle. A major aim for the program, in addition to fundamental research focused on physical science issues, is to improve the planning and decisionmaking protocols related to the management of natural and man-made resources and decisionmaking relevant to societal concerns. The program also aims to improve the science for

advancing regional and local analyses that are likely to be required for the development of climate change mitigation and adaptation strategies. To address such needs stemming from both the research and applications communities, several initiatives will be launched in FY 2010. Selected highlights of the plans follow.

Atmospheric Radiation Measurement (ARM) Science Program. In 2010, the ARM Science program will continue its focus on clouds, radiation, and aerosols with a particular emphasis on improving cloud-radiative and cloud-aerosol interactions and associated feedbacks in climate models. These are high-priority science topics, as also identified in the IPCC Fourth Assessment Report. A primary USGCRP goal is to characterize the properties of clouds so that their representation can be improved in GCMs. Utilizing ARM measurements that are available up to 2010, the ARM science program is targeting three specific science areas: (1) aerosol indirect effects; (2) three-dimensional radiative transfer in clouds; and (3) deep convective clouds and cirrus clouds.

The ARM science program is promoting the use of large-eddy simulation cloud-resolving models, or limited area regional models, in addition to the GCMs, to understand complex aerosol-cloud-radiative interactions and effectively utilize fine-scale ARM measurements. Ultimately, improved or newly developed formulations tested at high resolutions will be scaled up to high- and coarse-resolution GCMs for further testing and evaluation. In particular, the ARM science program expects scientific advancement in understanding of aerosol indirect effects (primary and secondary) in the tropical, middle, and polar latitudes. This will be achieved via characterizing atmospheric aerosol and cloud properties and their mutual interactions and impact on atmospheric radiation utilizing ARM and other measurements (e.g., from A-Train and TRMM satellites) and assessing the representation of these properties in models.

ARM measurements will also be used to target some of the challenging problems associated with cumulus convection, including (1) how and when convection is initiated; (2) why climate models fail to mimic the observed nature of convection (diurnal cycle and frequency); (3) does a climate model have the ability to simulate convectively coupled tropical waves that are major sources of tropical storms; (4) how the deep convection affects the formation of cirrus clouds; and (5) whether the convection formulations currently used in climate models can be scaled to high-resolution climate simulations with sufficient accuracy to participate in the next IPCC simulations.

This activity will address Goals 1, 2, and 3, and Questions 5.1, 5.2, and 5.3 of the 2003 Strategic Plan

Next-Generation Space-Based Measurements of Critical Global Water Cycle Variables. Planning and instrument development continues for the two critical next-generation water cycle satellite platforms, namely the Global Precipitation Mission (GPM, the global follow-up to the demonstrably successful TRMM), and the L-Band Soil Moisture Active-Passive (SMAP) mission. The National Research Council's Decadal Survey endorsed the GPM and recommended the SMAP. The SMAP mission is aimed at global mapping of soil moisture and freeze/thaw states in order to understand processes that link the terrestrial water, energy, and carbon cycles; estimate global water and energy fluxes at the land surface; quantify net carbon flux in boreal landscapes; enhance weather and climate forecast skills; and develop improved flood prediction and drought monitoring capability. To provide these measurements the SMAP mission will use the combination of a high-resolution microwave radiometer and a radar with similar resolution. The scanning characteristics of these instruments will enable revisit times of two to three days. GPM will extend TRMM's observations of precipitation to higher latitudes, with more frequent sampling, and with focused research on providing a more complete understanding of the global hydrological cycle. GPM will be capable of measuring rain rates as low as a few tenths of mm to as large as 100 mm per hour. It will also be able to estimate the various sizes of precipitation particles, and discriminate between snow and rain. GPM will comprise a core central precipitation-measuring observatory with both a dual-frequency precipitation radar and a high-resolution microwave imager. The core will also serve as a calibration reference system. In addition to the core, a constellation of eight satellites will constitute the GPM sensor web, each carrying a single radiometer on board—identical to the core's microwave imager. The microwave radiometers on multiple satellite platforms will provide uniformly-

calibrated precipitation measurements to be made every 2 to 4 hours around the globe.

This activity will address Goals 1, 2, 3, and 4, and Questions 5.1, 5.2, and 5.3 of the 2003 Strategic Plan

Integration of Observations and Modeling—Atmosphere, Land Surface, and Subsurface Hydrology. From among existing or planned hydrological observatories operated by various agencies, the selection of approximately three to four sites for the establishment of integrated observational platforms for the terrestrial water cycle covering a range of hydroclimatic regimes will be completed with input from the Science Steering Group of the global water cycle program. Following site selection, a gap analysis is planned to suggest complementary observational instruments that may need to be installed to meet the science objectives of the water cycle program related to improving models that couple atmospheric, land surface, and subsurface hydrological processes and water/moisture transport fluxes. Improvements in this class of models are deemed necessary to improve the regional-to-local accuracy of dynamically downscaled climate prediction/projection model outputs and their application to water resources-related issues.

This activity will address Goals 1, 2, and 3, and Questions 5.1, 5.2, 5.3, and 5.4 of the 2003 Strategic Plan

Yukon River Basin Permafrost Thawing. Recent climate warming has accelerated permafrost thawing throughout the Yukon River Basin, making vast stores of previously frozen organic material available for hydrologic export to the Bering Sea or for decomposition and subsequent emission of carbon dioxide and methane to the atmosphere. Continued studies in the Yukon Basin will focus on the total input of dissolved organic carbon to the Arctic Ocean, which appears to be 5 to 20% greater than previously reported, and about 2.5 times greater than temperate rivers with similar watershed sizes and water discharge. Planned work by the USGS Water Resources National Research Program will examine the groundwater contribution to total annual flow. New and planned work suggests that the observed increases in groundwater contributions may be largely due to enhanced infiltration brought about by permafrost thawing.

This activity will address Goals 1, 2, 4, and 5, and Questions 5.2, and 5.4 of the 2003 Strategic Plan

Drought and Water Resources. During recent decades, droughts lasting one to three years have affected some parts of the United States, but prolonged droughts of the magnitude experienced during the 1930s and 1950s have not occurred. To help the country prepare to face the potential effects of a prolonged drought, USGS scientists, along with colleagues in universities and other government agencies, have been studying regional, national, and global distribution patterns of drought. Coping with a prolonged drought is anticipated to be difficult, particularly in the arid and semi-arid West, where water demand has increased significantly and water supplies are likely to be insufficient for demand during dry periods. In 2010, USGS scientists and their collaborators will publish studies examining historic and predicted streamflow in the Colorado River Basin, estimate impacts of 21st-century warming on water availability, and develop projections based on climate change scenarios for the western United States.

This activity will address Goals 1, 4, and 5, and Questions 5.1, 5.4, and 5.5 of the 2003 Strategic Plan
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4 LAND USE AND LAND COVER CHANGE

Strategic Research Questions

6.1 What tools or methods are needed to better characterize and current land use and land cover attributes and dynamics?

6.2 What are the primary drivers of land use and land cover change?

6.3 What will land use and land cover patterns and characteristics be 5 to 50 years into the future?

6.4 How do climate variability and change affect land use and land cover, and what are the potential feedbacks of changes in land use and land cover to climate?

6.5 What are the environmental, social, economic, and human health consequences of current and potential land use and land cover change over the next 5 to 50 years?

See Chapter 6 of the *2003 Strategic Plan* for detailed discussion of these research questions.

The global climate system is affected by land use and land cover changes through biogeophysical, biogeochemical, and energy exchange processes. These changes in turn affect climate at local, regional, and global scales, through direct effects as well as indirectly through ecosystem shifts and social and economic drivers of land use change. Through joint solicitations and interagency coordination, USGCRP researchers are making progress in uncovering and understanding these effects and interactions, and in developing better predictive models of land use and land cover change to link carbon, ecosystem, climate, and Earth systems models.

Key climate-linked exchange processes include uptake and release of greenhouse gases to and from the atmosphere by the land cover of the terrestrial biosphere through photosynthesis, respiration, and evapotranspiration; the release of aerosols and particulates from surface land cover perturbations; variations in the exchange of sensible heat between the surface and atmosphere due to land cover changes; variations in absorbance and reflectance of radiation as land cover changes affect surface albedo; and surface roughness effects on atmospheric momentum that are dependent on land cover. Furthermore, these exchange processes are frequently linked with each

other. For example, changes in land cover modify the reflectance of the land surface, which determines the fraction of the sun's energy absorbed by the surface, thus modifying the available heat. These processes also alter vegetation transpiration and surface hydrology and determine the partitioning of surface heat into latent and sensible heat fluxes. At the same time, vegetation and urban structures determine surface roughness and thus air momentum and heat transport. In addition, land and land cover perturbations such as deforestation and forest fires alter ecosystems and release greenhouse gases and aerosols to the atmosphere.

The social science component of global climate research results in part from the fact that the human population lives in, depends upon, and is altering land cover and land use. At the same time, climate change is affecting land cover by changing abiotic variables, such as temperature and precipitation, that in turn directly affect human food and fiber production, energy use, and sea level rise. Thus, policy and management decisions directly affect land use and land cover change and hence climate. A rigorous research program in land use and land cover change not only quantifies important influences upon climate, but also forms the basis for subsequent human adaptation and mitigation efforts.

Research that examines historic, current, and future land use and land cover change, its drivers, feedbacks to climate, and its environmental, social, economic, and human health consequences, is therefore of great importance for understanding climate change and requires interagency and intergovernmental cooperation. Future land use and land cover change goals include (1) very accurate biomass estimates, thus refining our knowledge of carbon storage in vegetation and forests in particular; (2) understanding regional land use changes that affect biomass and greenhouse gas fluxes; and (3) quantifying linkages and feedbacks between land use and land cover change, climate change forcings, climate change, and other related human and environmental components.

HIGHLIGHTS OF RECENT RESEARCH

The following are selected highlights of recent research into land use and land cover change issues supported by USGCRP-participating agencies.

GLOBAL FOOD, FORESTS, AND FUEL

Global Agricultural Production Determination.[1] The USGCRP and scientists at academic institutions have collaborated in a study to improve agricultural monitoring and crop production estimation using the new generation of research satellite observations. The land use and land cover change component of this work involves determining what crops are being cultivated and then following these areas through time to estimate crop production at harvest. Because the work is global, this information is of use in understanding global food production. Use of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua research satellites has improved the food production estimates significantly. This study was made possible by the rapid availability of 250- and 500-m resolution time series of Normalized Difference Vegetation Index data provided by the MODIS instruments on the two research satellites. As global food production becomes increasingly strained from increasing population, rising standards of living, and the diversion of food crops to biofuels, timely quantitative information on global food production is crucially important. Due to increasing emphasis on biofuel production, this information is also important to the energy sector.

Completed National Land Cover Database (NLCD) for Alaska. USGCRP scientists working in conjunction with the interagency Multi-Resolution Land Characteristics (MRLC) Consortium have completed the 2001 National Land Cover Database (NLCD 2001) for Alaska. It represents the first time that 30-m cell land cover data has been produced for the state, and is part of MRLC's effort to produce land cover products for all 50 U.S. States and Puerto Rico. Land cover information is essential for addressing a wide variety of issues, such as assessing ecosystem status and health, understanding spatial patterns of biodiversity, understanding climate change, and developing effective land management policies. The NLCD is available for download from the MRLC web site at <www.mrlc.gov>.

Thirty Years of Land Cover and Land Use Change in Bolivia.[2] Land cover change in the eastern Bolivia lowlands was documented using Landsat images from five time periods (Landsat-1 and -2 for 1975-1976; Landsat-4 and -5 for 1985-1986 and 1991-1992; Landsat-7 for 2000-2001; and Landsat-5 for 2004-2005) for all landscapes situated below the montane tree line (~3,000 m), including humid forest, inundated forest, seasonally dry forest, and cloud forest, as well as scrublands and grasslands.

Satellite Monitoring of Crop Yields

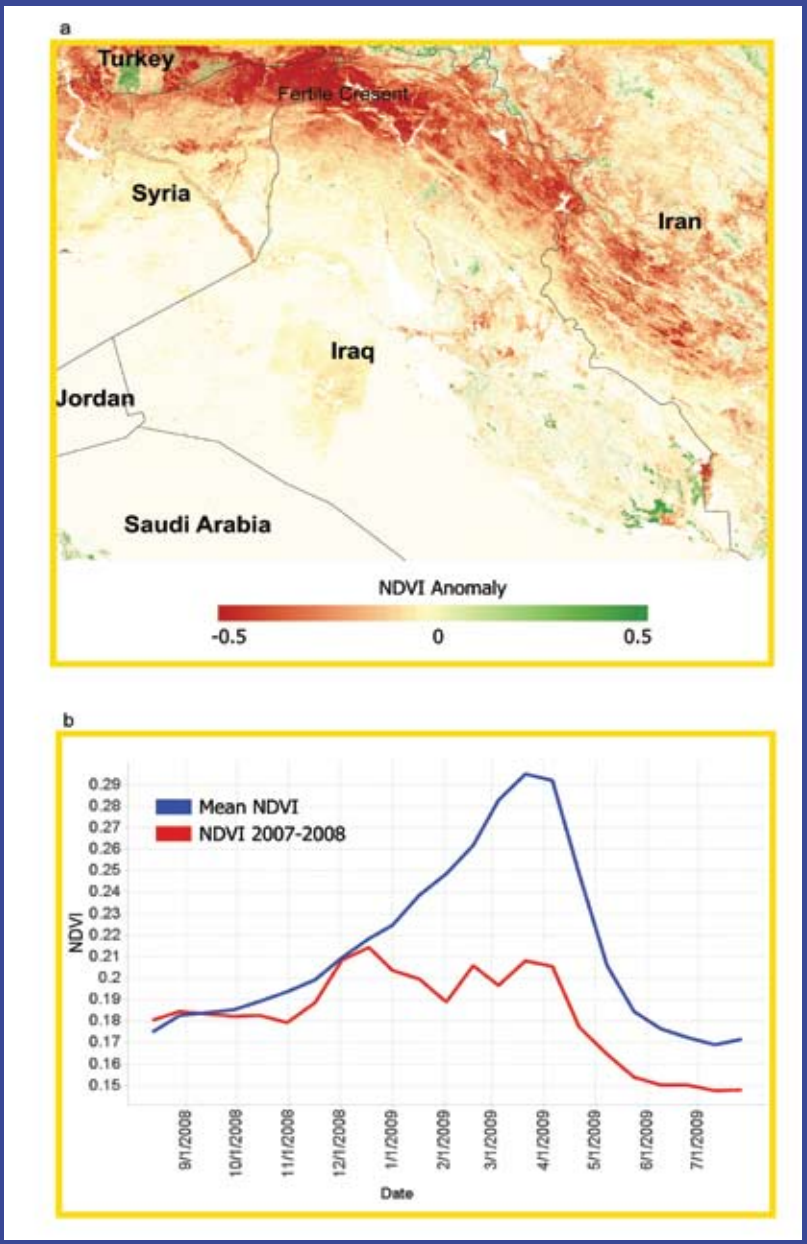

Figure 8: An example of crop monitoring using satellite data to determine agricultural production using MODIS instruments on research satellites. In a) an area of severe drought is identified in the Fertile Crescent of the Near East. In b) a comparison is made for all the cropped areas in Iraq between the 2000 to 2007 mean conditions and the 2007/2008 growing season. These data have proven to be extremely useful for monitoring global food production. *Credit: I. Reshef, University of Maryland.*

Deforestation in eastern Bolivia in 2004 covered 45,411 km^2, representing about 9% of the original forest cover, with an additional conversion of 9,042 km^2 of dry forest, scrub and savanna habitats representing 17% land cover change of these ecosystems. Annual rates of land cover change increased from about 400 km^2 yr^{-1} in the 1960s to about 2,900 km^2 yr^{-1} in the last time period (2001-2004). This study provides Bolivia with a spatially explicit information resource to monitor future land cover change, a prerequisite for proposed mechanisms to compensate countries for reducing carbon emissions as a result of deforestation. A comparison of the most recent period with previous periods shows that policies enacted in the late 1990s to promote forest conservation had no observable impact on reducing deforestation and that deforestation actually increased in some protected areas. The rate of land cover change continues to increase nationwide, and is growing at near exponential levels in the Santa Cruz Department due to the expansion of mechanized agriculture and cattle farms.

Changes in Forest Type, Cover, and Productivity

Aboveground Biomass of Northern Forests will be Restricted by Climate Change.[3] As climate warms in the Northern Hemisphere, a northward migration of tree species adapted to a warmer climate is expected. If this migration lags behind the rate of climatic change, overall growth rates and above ground biomass of northern forests may be significantly reduced relative to their potential. Using a spatially interactive forest landscape model, LANDIS-II, researchers simulated multiple scenarios of disturbance and climatic change across a roughly 15,000 km^2 forested landscape in northwestern Wisconsin. The results indicated a reduction in aboveground live biomass relative to the potential biomass for the combined soils and changing climate conditions. Species migration and range expansion were adversely affected by habitat fragmentation that makes it more difficult for species to migrate. The

Patterns of Deforestation

Figure 9: Oblique photograph of a radial pattern of deforestation near San Javier in the Santa Cruz Department of Bolivia, where tropical seasonal or deciduous forest is being cleared for agriculture. This radial pattern of land use is typical of new settlements where people from the Altiplano are being relocated to the lowlands of Bolivia. *Credit: C.J. Tucker, NASA/Goddard Space Flight Center.*

abundances of some tree species were also significant predictors of species migration and range expansion and indicated significant competition between existing species assemblages and more southerly species that are expected to migrate northward.

Land Cover Change Trends have Strong Affect on Magnitude of Carbon Sink in Northeastern Ecoregions of North America.[4] Land cover change is a key driving force behind carbon dynamics. A study was conducted of land use and land cover trends for the period 1975 to 2025 in the Laurentian Plains and Hills ecoregion of Maine and eastern Canada using sequential remotely sensed land cover observations in combination with a biogeochemical model. The model used was the General Ensemble Biogeochemical Modeling System (GEMS). Observations of major land cover changes from randomly located 10x10 km blocks were assimilated into the model, incorporating data based on the Forest Inventory and Analysis (FIA) and the U.S. General Soil Map (STATSGO). Results indicate that the Laurentian Plains and Hills ecoregion forests have been sequestering 4.2 teragrams of carbon (TgC; 1 teragram = 10^{12} grams) per year, including 1.9 Tg C removed from the ecosystem as a consequence of deforestation.

Scientists Reconstruct Historical Land Cover and Biophysical Parameters in the Eastern United States: Studies of Land-Atmosphere Interactions.[5] The eastern United States has experienced drastic land cover changes since 1650 from land clearing and deforestation, wetland drainage, intensive land use, urban expansion, forest regrowth, intensive agriculture, and landscape fragmentation, altering the biophysical properties of the land surface that control land-atmosphere fluxes of water, energy, and carbon. By combining several data sets and public historical information on land cover, scientists developed and analyzed land cover and biophysical parameter data sets for the eastern United States for four slices of time (1650, 1850, 1920, and 1992) in order to understand the potential implications of these land use transformations and characterize the historical diversity and distribution of land surface properties. Time series maps of land surface albedo, leaf area index, a deciduousness index, canopy height, surface roughness, and potential saturated soils over this period

illustrate the profound effects of land use change on the biophysical properties of the land surface. Although much of the eastern forest has returned, the average biophysical parameters for recent landscapes remain markedly different from those of earlier periods. With respect to 1650 estimates, for example, deciduousness and albedo remain higher, while canopy height, peak-season leaf area index, surface roughness length, and potential soil moisture saturation remain considerably reduced. Understanding the consequences of these historical changes will require modeling experiments that explore land-atmosphere interactions.

Irrigation and Cropland Management in the Midwestern United States

Increase in Near-Surface Atmospheric Moisture Content due to Land Use Changes.[6] Land use change can significantly affect root zone soil moisture, surface energy balance, and near-surface atmospheric temperature and moisture content, which have a major impact on evapotranspiration and energy balance and therefore temperature and regional climate. During the last half of the 20th century, irrigation was extensively used in the northern Great Plains and continues to increase. Scientists in Nebraska analyzed observed dew point temperatures (Td) to assess the effect of irrigated land use on near-surface atmospheric moisture content, using data from the Automated Weather Data Network of the high plains. Long-term daily Td data from 6 non-irrigated and 11 irrigated locations were analyzed. Results suggest an increase in growing season Td over irrigated areas by an average of 1.56°C. The higher evapotranspiration rates in irrigated areas at the peak of the growing season led to a cooling of up to 1.41°C during the growing season.

Assessing Crop Residue Cover.[7] Greenhouse gas and carbon balance in agricultural fields are strongly influenced by crop residue on the soil surface over the course of the year. Current methods of measuring residue cover are inadequate for characterizing the spatial variability over many fields because estimates from remote sensing are affected by varying residue moisture conditions and soil type. A new reflectance ratio water index, based on two bands near the cellulose absorption area, has been tested on corn, soybean, and wheat fields. This index was used to describe the moisture-induced changes in the crop residue cover/cellulose absorption index relationship, allowing spatial and temporal adjustments to spectral estimates of crop residue cover and thus improving crop residue cover predictions. Tests indicated that spatial and temporal adjustments in the spectral estimates of crop residue cover were possible and regional surveys of the adoption of conservation practices that affect crop residue cover are feasible using advanced aircraft- and satellite-based remote-sensing imaging systems.

Socioeconomic-Ecological Effects and Drivers

Analysis by Scientists and Resource Economists Foresee Land Use Changes with Climate Change.[8] Research by an interdisciplinary team of economists and agricultural scientists led to several conclusions regarding land use and climate change based on economic and ecological analyses. These included commodity price, leakage (specifically, net GHG emission reductions within one region being offset by increased emissions from expanded deforestation in other areas of the world), and market consequences of a biofuel expansion in the United States. The projected expansion of biofuels resulted in threats to South American rainforests and shifting loci of overall agricultural production within the United States. Climate change will put additional stress on the fragile northeastern U.S. dairy industry and small family farms with limited resources to invest in adaptation strategies. Climate change will also affect bark beetle outbreaks, wildfire occurrence, and invasions of alien plant species, along with the productivity and health of forest ecosystems.

Implications of City Growth Rates, Economic Status, and Resource Availability on Microclimate in Urbanizing Desert Areas.[9] USGCRP-sponsored researchers have developed new approaches to provide more useful spatial-temporal representations of changes in water use and water availability under climate change scenarios. Important biophysical feedbacks discovered were (1) the effect of city growth on the urban heat island effect of Phoenix, and (2) socio-ecological influences manifested through household decisions about water use and how that in turn affected regional water demands. Satellite data for surface temperatures revealed the cooling effect of some kinds of plant cover in urban areas, with more densely planted vegetation having cooler surface air temperatures. In addition, wealthier areas were associated with more vegetation and lower temperatures. These results show that land use decisions affect microclimate and resource availability. In turn, how people live and their wealth and goals affect land cover, which also then affects climate. These findings have implications regarding the

interactions between urbanization patterns and global change.

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAPs most relevant to Land Use and Land Cover Change and completed during the period of this report are as follows:

SAP 4.3: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States (2008)

SAP 5.1: Uses and limitations of observations, data, forecasts, and other projections in decision support for selected sectors and regions (2008)

HIGHLIGHTS OF PLANS FOR FY 2010

The FY 2010 interagency priority for this USGCRP research element is to better quantify land use and land cover change interactions with climate change. Research will include studies of feedbacks and adaptation to change, in order to improve understanding of cascading effects and thus improve predictive capability. The following describes plans to address this priority.

Focus on Land Use And Land Cover Change-Carbon Cycle Interactions. The USGCRP land use and land cover, and carbon cycle interagency working groups convened a joint workshop in June 2009 to bring together scientists in these interdisciplinary science communities to share research results, identify uncertainties, caucus on future research directions, and foster new collaborations across agencies and disciplines. Results from this workshop, in the form of a workshop report and a book-length manuscript, will be prepared in FY 2010 in order to guide a new initiative and collaborations focusing on the development of an explicit carbon cycle representation for land use and land cover change studies.

This activity will address Goals 1, 2, 3, and 4, and Questions 6.1, 6.3, 6.4, 6.5, 7.3, 7.5, and 7.6 of the 2003 Strategic Plan.

Planning for Global Land Survey (GLS) 2010 Satellite Data Project.[10] Following the success and wide use of the GLS 2005 reprocessed data set (the 1970s, 1990, 2000, and 2005), planning is underway to add global Landsat data from 2010 to the previous GLS 2005 data set. Imagery obtained through the GLS 2010 project will be used to assess large-area rates of land cover change, both by

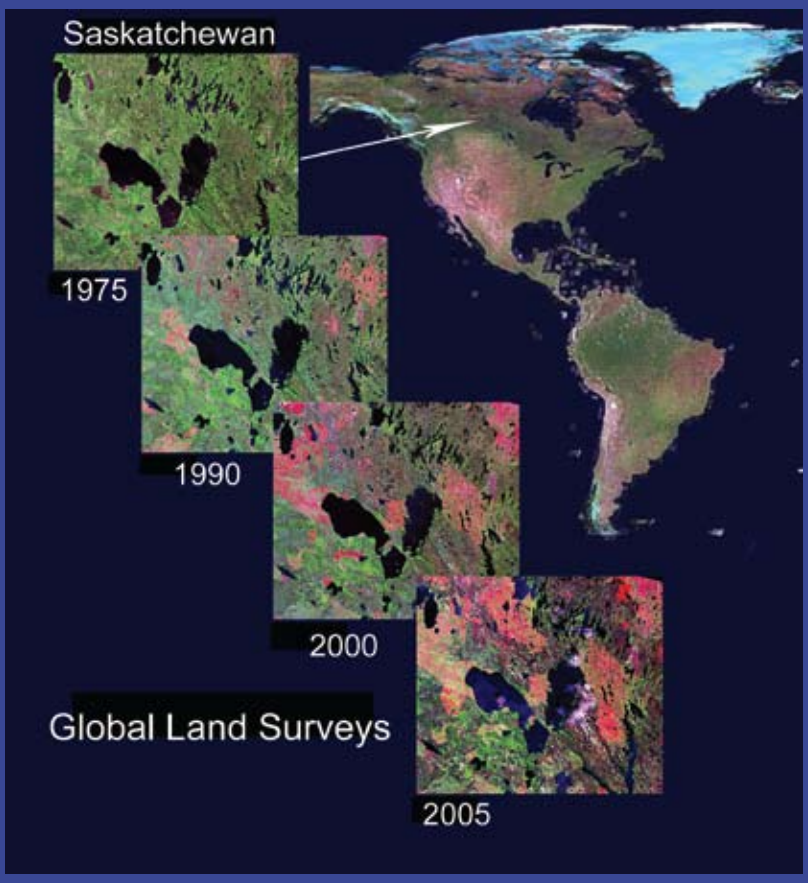

Figure 10: Examples of the GLS 2005 images for Saskatchewan. These images illustrate the four data layers in this global data set of Landsat imagery: the 1970s, 1990, 2000, and 2005. All four data layers were geometrically corrected to the terrain using the 2000 Landsat-7 data layer as the rectification basis. These data are now being distributed free of charge through NASA and the USGS. *Credit: G. Gutman, NASA/Headquarters; J. Masek, NASA/Goddard Space Flight Center; C. Justice and S. Franks, University of Maryland; R. Byrnes and R. Headley, USGS.*

international programs and through projects funded by multiple USGCRP agencies. The collaborating USGCRP agencies formally agreed to produce a geometrically corrected global Landsat-based data set as part of the GLS 2010 initiative, similar to that generated for GLS 2005. This represents the U.S. contribution to the international GLS 2010 initiative, in which several national space agencies have been requested to provide input to a jointly assembled set of quasi-global and regional data to produce global geographic coverage from Landsat-class sensors. Given the limited capabilities of the current Landsat sensors, the GLS 2010 will include an international component organized through the Committee on Earth Observation Satellites (CEOS) Land Surface Imaging Constellation. It is hoped that the new data set will include contributions from other operators of mid-resolution remote-sensing missions. This data set will provide significant input to various international initiatives, such as the Food and Agriculture Organization's decadal Forest Resource Assessment.

This activity will address Goals 1, 2, and 4, and Questions 6.2, 6.3, and 6.4 of the 2003 Strategic Plan

Environmental Effects of Biomass-Based Energy. USDA and DOE are coordinating on a competitive research program in biomass research and development over the next five years. The research areas will include the environmental impacts of expanded biofuel production and the implications for land use and land management changes, including forest, crop, range, and Federal lands.

This activity will address Goal 5 and Questions 6.4 and 6.5 of the 2003 Strategic Plan.

Precision Conservation Using Multiple Cellulosic Feedstocks. The Agricultural Research Service in South Dakota is conducting research to develop site-specific guidelines for conservation to assure sustainable production as land use moves toward increased cellulosic biomass for energy production. The Natural Resources Conservation Service and the Cooperative Extension Service will develop technical guidelines and fact sheets for use by developers and land managers.

This activity will address Goal 5 and Question 6.5 of the 2003 Strategic Plan.

Integrating Climate and Land Use: Development of Land Use Scenarios Consistent with Emissions Storylines.[11] Climate change interacts with existing and future land uses, but until now, there have been no scenarios of land use changes for the United States that are consistent with emissions storylines used by climate change modelers. The lack of consistent scenarios has hindered integrated assessments of climate and land use change. A methodology was developed to construct land use scenarios by decade from 2000 to 2100 consistent with these storylines for the conterminous United States. A demographic model is coupled with a housing allocation model to distribute new housing across the landscape. Housing density is also converted to impervious surface cover to facilitate water quality-related analyses. Results include regional trends in population growth and in housing density. The new methods developed are consistent with future scenarios of the 21st century and will be used in improved model studies.

This activity will address Goals 2, 3, and 4, and Questions 6.2, 6.3, 6.4, and 6.5 of the 2003 Strategic Plan.

Modeling Processes of Climate-Land Interactions. A Forest Service modeling effort focuses on how changes to forests and other land surfaces feed back to the climate system. The goal is to quantify and integrate physical and biological processes that are affected by forest management, and land use activities that potentially drive climate variability and change. The approach refines and improves land-surface albedo parameterizations in the Community Climate System Model (CCSM3) and other climate models. The improved land-surface albedo parameterizations will be used to evaluate the sensitivity of the climate system to afforestation and reforestation scenarios.

This activity will address Goals 1, 2, and 3, and Questions 6.4 and 6.5 of the 2003 Strategic Plan.

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5 GLOBAL CARBON CYCLE

Strategic Research Questions

7.1 What are the magnitudes and distributions of North American carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

7.2 What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

7.3 What are the effects on carbon sources and sinks of past, present, and future land use change and resource management practices at local, regional, and global scales?

7.4 How do global terrestrial, oceanic, and atmospheric carbon sources and sinks change on seasonal to centennial timescales, and how can this knowledge be integrated to quantify and explain annual global carbon budgets?

7.5 What will be the future atmospheric concentrations of carbon dioxide, methane, and other carbon-containing greenhouse gases, and how will terrestrial and marine carbon sources and sinks change in the future?

7.6 How will the Earth system, and its different components, respond to various options for managing carbon in the environment, and what scientific information is needed for evaluating these options?

See Chapter 7 of the *2003 Strategic Plan* for detailed discussion of these research questions.

The U.S. Carbon Cycle Science Program is progressing in understanding the changes, magnitudes, and distributions of carbon sources and sinks, the processes within and among major terrestrial, oceanic, and atmospheric carbon reservoirs, and the underlying mechanisms involved including human activities, fossil fuel emissions, land use, and climate forcings. Program scientists are currently uncovering and quantifying many of the intricate complexities and interactions between the major carbon reservoirs influencing climate. The program engages numerous Earth science disciplines and extends over a broad range of spatial and temporal scales. To execute this enormous undertaking, agencies and departments across the Federal Government with carbon cycle interests joined forces with the science community to coordinate, manage, and support the science and implementation plans for the North American Carbon Program (NACP), the Ocean Carbon and Climate Change (OCCC) Program, and Carbon North America (CarboNA) described later in this chapter. As agency investments for the first research priorities of the science programs evolve and generate local, regional, and global carbon observations, field and experimental results are assimilated to constrain advanced regional and global carbon cycle models.

U.S. CARBON CYCLE SCIENCE PROGRAM

The U.S. Carbon Cycle Science Program contributes to all of the overarching goals of the 2003 Strategic Plan, focusing particularly on Goal 2: Improved quantification of the forces bringing about changes in the Earth's climate and related systems. The Carbon Cycle Science Program directly addresses the six overarching questions of Chapter 7 (Global Carbon Cycle). The research element is synergistic with the Ecosystems, Water Cycle, Climate Variability and Change, Atmospheric Composition, Land Use/Land Cover Change, and Human Contributions and Responses/Decision Support research elements. The agencies responsible for carbon cycle research are DOE, NASA, NIST, NOAA, NSF, USDA Agricultural Research Service, USDA Cooperative State Research, Education, and Extension Service, USDA Forest Service, USDA National Resources Conservation Service, and DOI/USGS. Together, they have planned and are coordinating a multidisciplinary research strategy to integrate the broad range of needed infrastructure and resources, scientific expertise, and stakeholder input essential for program success and improved decisionmaking processes.

THE NORTH AMERICAN CARBON PROGRAM

NACP is designed to address strategic research question 7.1, and elements of questions 7.2 through 7.6 in Chapter 7 of the *2003 Strategic Plan*. For example, NACP research and modeling efforts will quantify the magnitudes and distributions of terrestrial, freshwater, oceanic, and atmospheric carbon sources and sinks for North America and adjacent coastal oceans; enhance understanding of the processes controlling source and sink dynamics; and produce consistent analyses of North America's carbon budget that explain regional and continental contributions and year-to-year variability. This program is committed to reducing uncertainties related to quantifying the increase of carbon dioxide and methane in the atmosphere and the amount of carbon, including the fraction of fossil fuel carbon, being taken up by North America's ecosystems and adjacent coastal oceans.

THE OCEAN CARBON AND CLIMATE CHANGE PROGRAM

OCCC Is designed to address strategic research question 7.2, and elements of questions 7.3 through 7.6 in Chapter 7 of the Strategic Plan. For example, in regards to question 7.2, the OCCC program will focus on oceanic research aimed at quantifying how much atmospheric carbon dioxide is being taken up by the ocean at the present time and how climate change will affect the future behavior of the oceanic carbon sink. The terrestrial and ocean carbon programs are synergistic, integrating program activities that address carbon dynamics at the land/sea interface and on continental shelves adjacent to North America (7.1 and 7.2), where carbon changes in the terrestrial system greatly influence carbon processes in the coastal ocean.

In FY 2010, the Carbon Cycle Science Program will extend the recently initiated research priority on high latitudes. This research includes quantifying the magnitude and dynamics of high-latitude carbon sources, sinks, and fluxes associated with ecosystems during a period of rapid climate change, and achieving greater integration of research and models between the NACP and OCCC programs. To accomplish these objectives, the USGCRP agencies are soliciting new investments and reprogramming previous research investments to augment ongoing carbon observations and networks, field studies, data analysis, and modeling research for high-latitude terrestrial and aquatic ecosystems, as well as to identify and fill gaps.

As current carbon cycle research programs evolve, scientific and governmental collaborations are broadening with Canada and Mexico (affiliated with NACP and OCCC), and internationally with partner countries in the Northern Hemisphere encompassing global carbon scientific and management interests.

HIGHLIGHTS OF RECENT RESEARCH

Research highlights that follow are selected accomplishments of the U.S. Carbon Cycle Science Program. These accomplishments span carbon cycle topics related to climate forcings, terrestrial and oceanic sinks and sources, the atmospheric reservoir, global carbon analysis, carbon management, and other relevant biogeochemical exchanges between major Earth reservoirs that link to climate.

Climate Forcing

Carbon dioxide (CO_2) and methane (CH_4) gases are major forcing agents of climate, and concentrations have been increasing in the atmosphere over the past two centuries as a result of human activities.[1] Approximately 80 to 85% of today's anthropogenic emissions are due to fossil fuel combustion, with land use change accounting for most of the rest. Future concentrations of these carbon-containing gases in the atmosphere will depend on the short- and long-term forces affecting terrestrial and oceanic reservoirs, the rate of exchange between major reservoirs, the variability in natural and anthropogenic emissions, and the capacity of natural and managed sinks.

Forest Disturbance Effects on the Carbon Budget.[2,3] Landsat data were used to quantify changes in forest cover and disturbance for the North American continent during the period 1990 to 2000. Disturbances due to logging, as well as fire, insects, and storms, are pervasive in the southeastern United States, Quebec/Maine region, and Pacific Northwest (Figure GCC-1). In these regions, 2 to 3% of forest cover is disturbed annually. Nationally, about 0.9 ± 0.2% of U.S. forest is estimated to be disturbed annually. These disturbance events may play an important role in varying terrestrial carbon fluxes that may have previously been attributed primarily to climate change. The results are currently being employed to refine models of terrestrial carbon fluxes. Work is ongoing to estimate rates of biomass accumulation in recovering forests from spectral and temporal trajectories and to

Forest Disturbance Mapped from Space

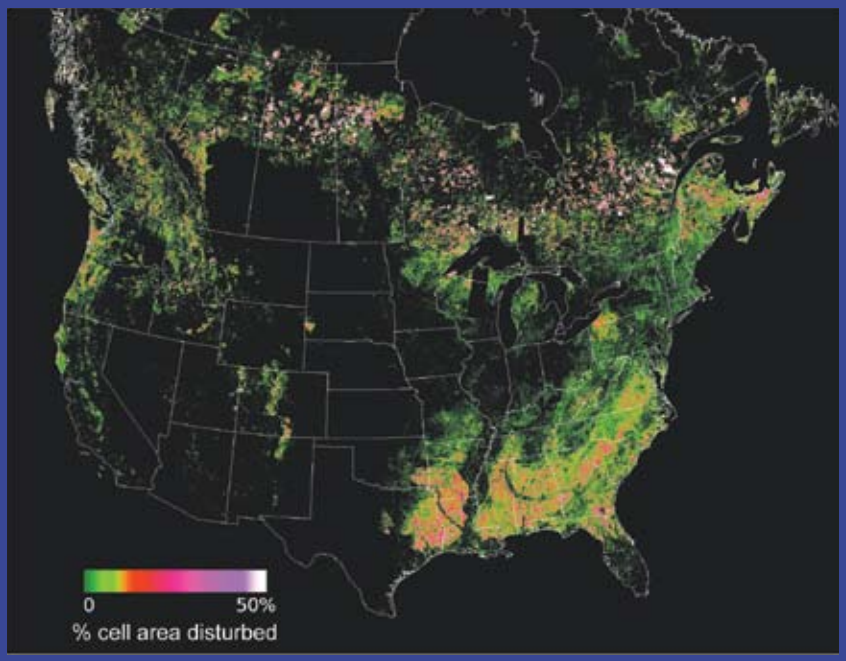

Figure 11: North American forest disturbance intensity, 1990 to 2000, mapped from about 2,200 Landsat images. Colors represent the percent of each 500 x 500 m cell disturbed during the mapping period. *Credit: J. Masek, NASA/ Goddard Space Flight Center.*

estimate directly the amount of carbon being taken up by forests during early regrowth.

Seasonal Climate Effects on Forest Carbon Balance.[4,5] The seasonal distribution of temperature and precipitation may be as important to carbon balance in forests as the actual temperature and amount of precipitation. The carbon balance of terrestrial ecosystems depends on both the rate of carbon sequestration (via photosynthesis) and the rate of carbon emission (respiration giving off CO_2). An international research team found that global warming increases spring photosynthesis more than spring respiration at high latitudes. However, warming in autumn increases respiration more than photosynthesis, offsetting about 90% of the spring increase in carbon sequestration. Rainfall patterns during spring leaf out can also affect carbon sequestration. When drought occurred during bud break, the carbon sequestered for the entire year was reduced by 40% compared to a year with normal rainfall during that period. Researchers found that drought during leaf out had little effect on respiration, which continued at normal rates, but suppressed photosynthesis, due to decreases in quantum yield, canopy conductance, and leaf area. Such droughts, beginning more than one or two weeks before bud break, are likely to impair annual productivity in the region.

Terrestrial Carbon

The terrestrial system comprises a complex set of interactive biogeochemical cycles that transfer carbon among land, oceans, and the atmosphere. Collectively, terrestrial biogeochemical processes influence atmospheric concentrations of CO_2 and CH_4. Improving scientific understanding of the role of terrestrial reservoirs and processes in the carbon cycle reduces the uncertainty in the factors influencing greenhouse gas increases and provides a stronger foundation for climate change decision support, in particular for carbon management to mitigate CO_2 and CH_4 increases in the atmosphere.

Mature Forests Continue to Sequester Carbon and Therefore Should be Included in Future Carbon Offsets.[6] An international research team showed that, contrary to conventional wisdom, old-growth forests (≥150 years) absorb more CO_2 from the atmosphere than they release annually, thus helping to mitigate the increase of CO_2 in the atmosphere. Based on a global data set from several measurement networks (e.g., CarboEurope, AmeriFlux), researchers found that old forests can continue to accumulate carbon and sequester about 1.3 ± 0.5 GtC yr^{-1}. Over 30% of the global forest area is unmanaged old-growth forest, with half located in boreal and temperate regions of the Northern Hemisphere. The study estimated that this 15% of the global forest area accounts for 10% of the global net uptake of CO_2. If these forests are disturbed, much of the stored carbon, including soil carbon, will be released to the atmosphere. Avoiding deforestation is under discussion (Reducing Emissions from Deforestation in Developing Countries—REDD—a mechanism for compensating countries for reducing emissions from deforestation and forest degradation), but it is limited to the tropics, whereas this study suggests that old-growth forests in temperate and boreal zones should be included in future carbon offsets.

Carbon Balance in Forest Ecosystems: Carbon Accumulation and Soil Processes.[7,8,9] Biogeochemical models linking primary productivity with soil carbon predict that increased production will increase soil carbon storage. Recent research shows that the loss of soil-sequestered carbon is influenced by the type and amount of carbon inputs, changes in soil microbial communities, and interactions with growing roots. Live roots may inhibit decomposition by as much as 50% or accelerate it by as much as 300%, and this effect is correlated with leaf biomass and/or live root nitrogen levels. By varying above- and below-ground inputs, other research showed that soil carbon sequestration is not likely to increase with increases in aboveground litter production in eastern deciduous forests, while litter made significant contributions to soil carbon in Pacific Northwest coniferous forests. In either case, microbial activity could be stimulated by increased carbon inputs, accelerating loss of long-term stored soil carbon. These complex interactions among terrestrial primary productivity and carbon storage, and microbial and root responses, need to be taken into account in carbon models.

First Synoptic Continental-Scale Measurements of CH_4 and Nitrous Oxide.[10] Using a regional inverse modeling approach, "top-down" estimates of nitrous oxide (N_2O) and CH_4 emissions were made using more than 300 measurements of N_2O and CH_4 collected

during two airborne circuits of North America in 2003. The top-down CH_4 fluxes agreed well with a combination of anthropogenic and natural bottom-up estimates. In contrast, for N_2O, the top-down results indicated that the N_2O bottom-up results were low by a factor of 2.6. The significance of this study lies in its demonstration of the value of independent, top-down (atmospheric) approaches to aid in evaluating and/or constraining estimates of emissions derived from the more traditional bottom-up (surface-level) approaches.

Oceanic Carbon

The global ocean is a large and important carbon reservoir on Earth that regulates the uptake, storage, and release of CO_2, CH_4, and other climate-relevant chemical species to the atmosphere. The future biogeochemical behavior of this reservoir is quite uncertain because of potential anthropogenic impacts on many ocean processes. Of particular concern is the impact of ocean circulation on carbon fluxes among land, ocean, and the atmosphere, as well as the impact of ocean acidification on the physiology, function, structure, and health of the biologically diverse ocean ecosystems.

Ocean Acidification[11] The oceans have absorbed approximately 146 GtC as CO_2 from the atmosphere, or about one-third of the total anthropogenic carbon emissions since the beginning of the industrial revolution. However, the ocean's uptake of CO_2 is lowering seawater pH and thus having negative impacts on the chemistry and biology of the oceans. For example, the time series data at ocean Station ALOHA (A Long-Term Oligotrophic Habitat Assessment) show an average pH decrease of approximate 0.02 units per decade in the northeast Pacific and the pH of Pacific Ocean surface waters has already decreased by about 0.11 units over the interval from 1987 to 2007. Estimates of future atmospheric and oceanic CO_2 concentrations would result in an additional surface water pH decrease of approximately 0.3 pH units by 2100.

Release of Methane from Clathrates.[12] Vast amounts of CH_4 are stored as clathrates in permafrost and beneath coastal ice sheets (Figure GCC-3a). As a greenhouse gas, CH_4 is about 30 times more potent than CO_2, and there is concern that climate warming and the melting of polar ice could cause the rapid release of CH_4 and serve as a positive feedback to further climate change. Researchers collected marine sediments deposited 635 million years ago that provide information on the most abrupt and severe warming event in Earth history. Analyses of these sediments suggest that melting of ice sheets and glacial meltwater destabilized the clathrates and resulted in a gradual and then rapid release of CH_4. This CH_4 likely contributed as a trigger or positive feedback to a rapid transition from a very cold to a very warm climatic state.

Advances in Ocean Carbon Monitoring and Modeling.[13,14,15] A major impediment to understanding the functioning of the oceans is the difficulty of obtaining sufficient data to gain a representative view of its ever-changing nature. Satellite observations permit a broad view, but only of the surface of the ocean and only of selected variables, while ship-based research allows sampling of many

Ocean Acidification in the North Pacific

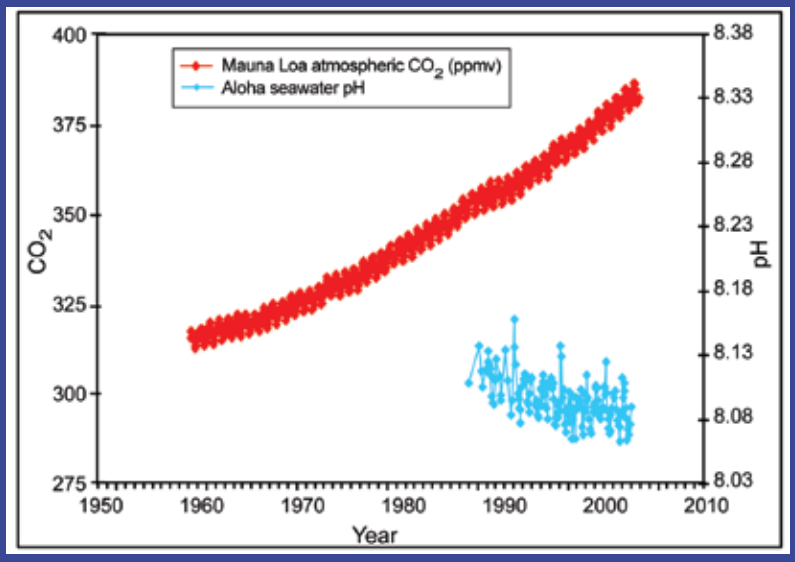

Figure 12: Time series of atmospheric CO_2 at Mauna Loa (ppmv) and surface ocean pH at Station ALOHA in the subtropical North Pacific Ocean. Note the overall decrease in surface water pH caused by dissolution of atmospheric CO_2 into the surface ocean. The variability in surface water pH is caused by seasonal changes and other oceanographic phenomena that affect pH on seasonal to interannual time scales. *Credit: R.A. Feely, NOAA/Pacific Marine Environmental Laboratory.*

Methane Release from Ancient Landforms

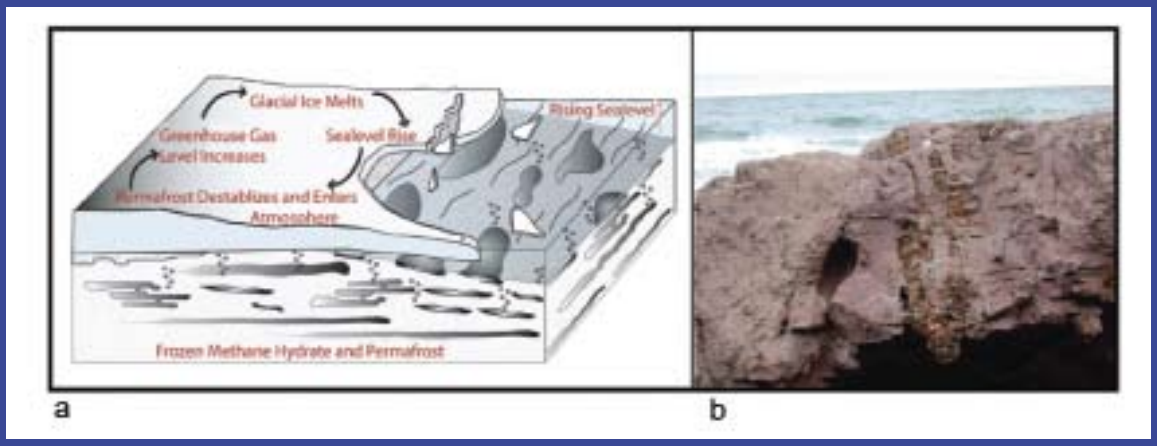

Figure 13: a) Conceptual diagram illustrates how glacial ice becomes unstable and begins collapsing en masse when pressure on underlying permafrost is reduced and CH4 is released into the atmosphere, initiating the positive feedback cycle shown, resulting in the possible release of 20 times the carbon in all estimated crude oil reserves. b) At the sea cliffs in South Australia, mineralized deposits (the yellow dolomite) from the fossil seeps are exposed within Precambrian tidal deposits. The yellow dolomite forms from a chemical reaction as the CH4 is oxidized in the sediment, providing a record of past methane release from the melting clathrates. *Credit: M. Kennedy and D. Mrofka, University of California, Riverside; and C. von der Borch, Flinders University.*

variables but only at very few times and places. Several innovative approaches have mitigated these difficulties. Float and glider technology has the potential to fill some of the gaps, and has matured sufficiently to survive deployment for three years in the subpolar North Atlantic Ocean. This deployment demonstrated close correspondence with a suite of satellite-derived observations and extended them deeper into the ocean. Coupled biogeochemical and physical models have also matured to a level where sophisticated approaches are required to assess their ability to realistically approximate oceanic processes. Comparison of such models to field and remotely sensed data revealed close correspondence for physical variables, good skill with chemical variables, and pointed to the need for improvement in biological variables. Exploration of the rarely visited southern Pacific Ocean has improved algorithms for an important component of ocean carbon, the particulate organic fraction. Advances on these different fronts will greatly benefit ocean carbon cycle studies and modeling in the future.

High-Latitude Systems

High-latitude systems are becoming increasingly important sources and sinks of atmospheric CO_2 and CH_4 as regional warming changes ecosystem dynamics in the cold regions. Understanding carbon dynamics in high-latitude systems and the factors that may lead to changes in those dynamics are crucial elements of global carbon modeling and essential for understanding the linkages and feedbacks among carbon reservoirs, ecosystems, land cover, hydrology, and climate variability.

Fire and Carbon Emissions in the Boreal Forest.[16,17,18] Vast quantities of carbon are stored in the boreal forests of northern latitudes, but forest fires can release large amounts of this carbon to the atmosphere as CO_2, thus contributing to further climate warming. A modeling study of the effects of climate and fire on forest composition and carbon balance over the past 60 years showed that climate had no net effect on carbon balance, whereas increased fire frequency during the late 20th century caused the boreal forest to change from a weak carbon sink to a weak carbon source. Modeling analyses also predict that the average area burned per decade in Alaska and western Canada will double by the middle of this century and triple or quadruple by the end of the century, further reducing carbon stored in boreal forest and increasing CO_2 in the atmosphere.

Carbon Stocks in Arctic Regions and Loss to the Atmosphere from Permafrost Melting.[19 20] Alaskan

researchers gathered data from 117 new sites and combined historical and modern data sets for soil organic carbon to estimate carbon stocks in the Arctic regions of North America. They calculated a total North American Arctic soil content of 98 GtC, equivalent to about one-sixth of the current content in the atmosphere and considerably higher than previous estimates. Climate warming may cause thawing of permafrost and release of this carbon to the atmosphere as a result of microbial decomposition. Climate change at northern latitudes can also result in enhanced carbon uptake—a negative feedback—as a result of increasing growing season length, increasing plant growth rates, species changes, and changes in surface energy balance. However, these negative feedback processes appear to be insufficient to balance the potential carbon release from thawing permafrost, suggesting a net release of carbon to the atmosphere that will contribute to further climate warming. In addition, permafrost soil thawing is releasing nutrients to rivers and basins that will increasingly affect nutrient cycling in the Arctic Ocean as more and deeper permafrost soils thaw. The dissolved and particulate organic carbon released from thawing permafrost soil is estimated to be several hundred to several thousand (up to 13,000) years old. This additional forcing from Arctic soil carbon release is not taken into account in current climate model projections.

Aquatic Carbon Cycling in the Yukon River Basin.[21,22] Thawing of permafrost has been hypothesized to result in the export of old or "^{14}C dead" dissolved organic matter from Arctic basins. However, studies of riverine export from throughout the Yukon River Basin and collaborative study of other Arctic basins indicate that this is currently not the case. While eroded particulate carbon in Arctic rivers has an aged component, most dissolved organic matter transported by the Yukon River and its major tributaries is of recent origin and is derived from terrestrial woody plants. In the Yukon River Basin, the bulk of the small fraction of old dissolved organic matter that is present originates from glacial headwater areas, not permafrost-dominated boreal forest or areas of extensive wetlands.

Fate of Carbon in Alaskan Landscapes.[23,24,25,26,27] Significant progress has been made on assessing changes in soil carbon in landscapes with degrading permafrost. In collaboration with several academic institutions, Federal scientists have been examining the potential to use the ^{14}C signature of microbial respiration from active layer and permafrost soils as an indicator of the inherent vulnerability of the soil carbon to decomposition. An online database of soil and gas ^{14}C measures is being established by the Critical Zone Exploration Network (CZEN) user group. In 2008, respired CO_2 from different ecosystem components was collected to determine if unique isotopic signatures exist that can be used to support scaling the different components of ecosystem respiration. Results indicate that the release of carbon from permafrost soils is highly dependent upon the number of dormant versus active microorganisms in these soils. Through small- and large-scale studies in Alaska, and through collaborative research across the Nation, scientists are seeking to improve our understanding of the vulnerability of soil carbon to climate change and disturbance.

Synthesis and Assessment Product

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAP most relevant to the Global Carbon Cycle and completed during the period of this report is as follows:

SAP 2.2: North American Carbon Budget and Implications for the Global Carbon Cycle (2007)

HIGHLIGHTS OF PLANS FOR FY 2010

Enhancing carbon cycle research, observational and experimental networks, and modeling efforts in high-latitude regions, along with continued integration of existing carbon cycle science programs and research results, will provide critical information to estimate carbon sources and sinks in North America and adjacent coastal ecosystems and ocean basins, thus diminishing uncertainties in the regional and global carbon budget. Research and network-based data will be assimilated in advanced regional and global carbon cycle models coupled to climate and Earth system models. Integration into Earth system analyses will allow assessment of the potential impacts of fossil fuel emissions and other forcing factors on terrestrial and ocean ecosystems, land cover and land use, and carbon management strategies.

High-latitude carbon cycle research. Tundra and permafrost soils cover a relatively small fraction of the Earth's surface but store nearly one-third of global soil carbon. Climate warming in interior Alaska is already causing some northern tundra to dry out, while other areas are becoming wetter. These changes could have a major effect on the carbon balance, including the potential release of sequestered CO_2 and CH_4 to the atmosphere. High-latitude waters are also affected by temperature increases causing a decline in local ice sheets and sea ice, which is beginning to affect oceanic primary producers that remove CO_2 from the atmosphere.

- *Yukon River Basin* – The Yukon River Basin Assessment and Pilot DOI Climate Effects Network identifies, detects, and monitors physical, chemical, and biological change related to changes in climate; identifies the processes controlling those changes; and seeks to understand and anticipate future changes to ecosystem services in interior Alaska. The Climate Effects node launched in the Yukon River Basin will concentrate on changes in water quantity and quality because of water's pivotal role in both temperature feedbacks and biological response. Process studies and site characterization are underway in one intensive study area. Methods for detecting change are being structured around remote-sensing products and mechanisms. The state and amount of water are being studied by a variety of ground, water, and air-borne measurement campaigns. Modeling and integration are integral to both intensive study area and regional scaling issues and are embedded in research components and tasks.
- *Siberian Carbon Measurements* – Federal scientists plan to report on new CH_4 measurements from Siberia, developed through collaborations with the University of Alaska and the Finnish Meteorological Institute at Cherskii and Tiksi, Russia. Measurements will be combined with CarbonTracker-CH_4[28] and a Lagrangian particle dispersion model to improve estimates of CH_4 emissions and the factors that determine emission rates from climate-sensitive permafrost regions.
- *Polar Ocean Carbon Research* – The polar oceans are expected to continue to experience rapid alteration in the coming decades due to temperature increases driving the decline of ice sheets, shelves, and sea ice. Improved understanding of these regions both in carbon cycle science and ecologically is required to understand the scope and extent of these changes on the ecology and chemistry of the ocean. A strong

ship-based field program in the Beaufort and Chukchi Seas and intensive use of satellite assets will be incorporated in a study of the effects of forcing factors such as changes in the amount of incoming solar radiation, sea ice extent, and acidification on ocean chemistry and ecology. Synthesis of field and satellite observations will enable combined physical and biogeochemical modeling studies of the region.

These activities will address elements of Goals 1, 2, 3, 4 and 5, and focus on Questions 7.1, 7.3, 7.4, and 7.5 of the 2003 Strategic Plan

North American Carbon Program. Agencies will continue to support integrative studies that significantly synthesize and extend results of carbon cycle research under the NACP, including results from past field campaigns.

- *Interim Synthesis Projects* – NACP investigators have organized four interim synthesis activities to evaluate and intercompare models and observations at local and regional scales for the period 2000 to 2005. 1) The Site Level Interim Synthesis is aimed at establishing a quantitative framework that allows NACP investigators to assess whether the various measurement and modeling estimates of carbon fluxes at individual sites are consistent with each other, and if not, why. 2) The Regional and Continental Synthesis will address the magnitude, spatial distribution, and interannual variability of carbon sources and sinks during the period 2000 to 2005 at regional and continental scales; whether model results and observations show a consistent impact of the 2002 drought; and how carbon sources, sinks, and our understanding of the underlying processes vary across scales. 3) The Mid-Continent Intensive (MCI) Interim Synthesis will compile, diagnose, and reconcile estimates of land-atmosphere CO_2 fluxes from

atmospheric inversions and bottom-up inventories (both measurement and model-based inventories, including process-based modeling), as part of the larger ongoing MCI activity. 4) The Non-CO_2 Greenhouse Gases Synthesis will examine the spatial and temporal distributions of CH_4, carbon monoxide, and nitrous oxide over North America.

- *Synthesis of CO_2 Exchange Data* – There are over 100 monitoring sites in forests across the globe, including those in the AmeriFlux network, that use eddy flux technology to continuously measure the rate and magnitude of CO_2 exchange between the ecosystems and the atmosphere. New techniques are being developed for integrating and analyzing the enormous amounts of data that have been produced by these sites. Data from 20 of these sites, distributed across a broad latitudinal gradient in the Northern Hemisphere, will be evaluated using an ecosystem process model. The large amount of data from these sites will be used to tightly constrain key parameters of the model. The resulting model will be applied to address two important issues. First, it will be used as a comparative tool to assess how controls over CO_2 exchange patterns differ across the 20 sites. Second, the sensitivities of CO_2 exchange to variations in the winter-to-spring climate transition will be evaluated. This transition is a key in the control of regional and global carbon budgets.
- *Greenhouse Gases and the Metagenome of Soil Microbes* – The conversion of natural ecosystems to agriculture affects the composition and functioning of soil microbial communities, including their production and consumption of greenhouse gases. Planned research will use the new science of metagenomics to understand how conversion from forests to farms affects the genomic structure of soil microbes involved in the consumption of two of these gases—N_2O and CH_4. There have been few such studies of soils, which may contain more than a million different microbial species per gram. Metagenomic data about soil microbes will be integrated with environmental characteristics and process-level measurements to link the genomic structure of soil microbial communities with ecosystem functioning. By making this link, the project offers the prospect of informing land management decisions such that management practices, which change the composition of microbial communities, mitigate rather than exacerbate detrimental increases in greenhouse gases.
- *A New U.S. Carbon Cycle Science Research Plan* – The 1999 U.S. Carbon Cycle Science Plan[29] promoted coordinated carbon cycle research across Federal agencies for nearly a decade. Building on this framework, subsequent reports, and program successes, a Carbon Cycle Science Working Group was charged with reviewing this science plan and developing an updated strategy to expand the carbon science to include research that is more responsive to decision support. Priorities identified in the initial plan will now be supplemented with additional focus on 1) the human component of carbon cycling, 2) the vulnerability of ecosystems to changes in carbon cycling and associated changes in climate, and 3) the efficacy and environmental consequences of potential carbon management policies, strategies, and technologies. Additional emphasis is also suggested for evaluating uncertainties in our understanding of the carbon cycle and coordinating researchers from different scientific disciplines to study a common problem.

These activities will address elements of Goals 1, 2, 3, 4 and 5, and focus on Questions 7.1, 7.3, 7.4, 7.5, and 7.6 of the 2003 Strategic Plan

Ocean Carbon and Climate Change Program. Agencies will continue to support integrative studies that significantly synthesize and extend the results of carbon cycle research under the Ocean Carbon and Climate Change program, including results from past field campaigns.

- *Ocean Carbon Observations* – Major ocean and coastal carbon programs will continue to cover regimes spanning ocean basins, coastal waters, and Great Lake ecosystems. New carbon and biogeochemistry programs will be announced with submission target dates in FY 2009 and 2010. These programs will be supported with reprogrammed investments in a wide range of ocean topics covering carbon cycling and biogeochemistry, including ocean acidification, river and coastal carbon exchange, and ocean carbon uptake and storage.
- *Large-scale Coastal Surveys* – Studies are continuing in the coastal regions of North America to study the movement of anthropogenic carbon and other tracers in coastal ocean waters. This is a comprehensive effort to measure partial pressures of CO_2 and related chemical and hydrographic measurements—dissolved inorganic carbon, alkalinity, oxygen, nutrients, and supporting physical measurements—over the entire coastal zone. The surveys will establish a

baseline of observational fields for carbon system parameters and develop a set of hydrographic transects with full water column measurements to be revisited over time for studies of seasonal to interannual changes in physical, chemical, and biological characteristics of the coastal ocean.

- *Ocean Carbon Modeling* – Two key climate processes will continue to be improved in ocean carbon modeling. The first is the role of the Southern Ocean in climate forcing. The research aims to quantify the rates of water mass transfer in the Southern Ocean associated with different circulations, to understand why water mass transformations differ greatly between models, and to analyze the relative contributions to numerical simulation uncertainties from physical and biogeochemical model components. The second is the capacity of the ocean to sequester carbon and continue to sequester it into the 21st century. The research addresses the nutrient limitation of CO_2 fertilization in the tropical oceans, which are among the regions with the greatest sources of uncertainty in the carbon cycle over the next half century.

These activities will address elements of Goals 1, 2, 3, 4 and 5, and focus on Questions 7.1, 7.2, 7.3, and 7.4 of the 2003 Strategic Plan.

Advancing carbon modeling. Agencies will continue research investments into developing new or improved regional and global carbon models that are more comprehensive in treating significant processes and drivers, including those involving or stemming from human activities. These advanced carbon models will address time scales of decades to centuries and integrate across spatial scales up to the global scale. One important focus for improving and extending the treatment of fundamental processes in carbon cycle models is to advance the coupling of global models allowing analyses of interactions and feedbacks within the coupled carbon and climate systems.

- *National Soil Carbon Network* – The emerging National Soil Carbon Network is a multi-component, science-based network to assemble databases, identify and fill gaps in data coverage, and through modeling and experimentation provide national, spatially explicit assessments of soil carbon turnover and change. This network will also play an important role in quantifying and modeling the spatial distribution of forms of carbon in the soil, and the effects of management, climate, and land use change on residence time of those forms.
- *Modeling Processes of Climate-Land Interactions* – A modeling effort will focus on how changes in forests and other land surfaces feed back to the climate system. The goal is to quantify and integrate physical and biological processes that are affected by forest management, and land use activities that potentially drive climate variability and change. The approach refines and improves land-surface albedo parameterizations in forest and other climate models. The improved land-surface albedo parameterizations will be used to evaluate the sensitivity of the climate system to afforestation and reforestation scenarios.
- *Global Carbon Cycle Modeling and Analysis* – New studies using satellite observations of CO_2 will document concentrations, sources and sinks, and atmospheric transport. Modeling research seeks to extend carbon data assimilation or data fusion schemes by incorporating models of major carbon cycle components with substantially improved detail, realism, and accuracy in the representation of key processes that determine magnitudes and distributions of sources and sinks for carbon and carbon cycle dynamics affecting CO_2 or CH_4 concentrations. The loss of the Orbiting Carbon Observatory (OCO) at its launch in February 2009 was a severe setback, but the research on the scientific underpinnings to make effective use of satellite CO_2 data will continue as the United States evaluates options for recovery. Research on atmospheric transport and inversion models and data assimilation and data fusion schemes that was being readied to utilize measurements of column CO_2 from OCO will be redirected to the utilization of other satellite data products, albeit products with less resolution and precision.

These activities will address elements of Goals 1, 2, 3, 4 and 5, and focus on Questions 7.1, 7.2, 7.3, 7.4, and 7.5 of the 2003 Strategic Plan.

Partnerships. Partnerships between scientists and governments are being strengthened to coordinate, synthesize, and interpret regional to global carbon data sets. In North America, the interagency working group along with Canada and Mexico created CarboNA and formed a CarboNA Science Steering Group and a Joint Government Coordination Team to lead and facilitate the common activities among the countries. To broaden U.S. efforts to encompass

the Northern Hemisphere, Federal and academic scientists are cooperating with national carbon programs in Western and Eastern Europe. Early activities with the European scientists include data management activities for global carbon observations, for example, the Coordination Action Carbon Observation System (COCOS). At the international organization level, the interagency working group is strengthening its collaboration with the Earth System Science Partnerships (ESSP) Global Carbon Project (GCP) through its U.S. Carbon Cycle Science Office functioning as the GCP Affiliate Project Office in North America. The international partnership is expected to enhance international interactions, regional syntheses, and significant deliverables on the global carbon budget, for example, the Regional Carbon Cycle Assessment and Process (RECCAP).

These activities will address elements of Goals 2, 3, and 4, and focus on Questions 7.4 and 7.5 of the 2003 Strategic Plan.

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6 ECOSYSTEMS

Strategic Research Questions

8.1 What are the most important feedbacks between ecological systems and global change (especially climate), and what are their quantitative relationships?

8.2 What are the potential consequences of global change for ecological systems?

8.3 What are the options for sustaining and improving ecological systems and related goods and services, given projected global changes?

See Chapter 8 of the *2003 Strategic Plan* for detailed discussion of these research questions.

The terrestrial and aquatic ecosystems that make up the biosphere provide a range of vital goods and services to humanity, including food, fiber, fuel, genetic resources, pharmaceuticals, cycling and purification of water and air, regulation of weather and climate, recreation, and natural beauty. Recent and ongoing global environmental changes—including climatic change, changes in atmospheric composition, land use change, habitat fragmentation, pollution, the extraction of natural resources, and the spread of invasive species—are affecting the structure, composition, and functioning of many ecosystems, and therefore the goods and services that they provide. In turn, many ecological effects of global environmental change have the potential to affect atmospheric composition, weather, and climate through both negative and positive feedback mechanisms. Because many global environmental changes are expected to increase in magnitude in the coming decades, the potential exists for increased effects of climatic change on ecosystems and the goods and services that they provide. Improved understanding and forecasting of potential effects of global change on ecosystems, as well as the feedbacks from ecosystems to global change processes, remains a USGCRP priority.

In FY 2010, the USGCRP Ecosystems Interagency Working Group (EcoIWG) will continue with its planning, implementation, and analysis of the results of research programs to accomplish the *2003 Strategic Plan* goals related to ecosystem research. EcoIWG will continue to focus on efforts to provide the scientific basis needed for better understanding of the interactions between climate and the physical, chemical, and biological forces that influence structure, composition, and functioning of ecosystems. These efforts will be essential in improving forecasts of the effects of climatic change on terrestrial and aquatic ecosystems, including the many goods and services that they provide. Research into ecological forecasting will take place at many scales, from local *in situ* experiments to national- and global-scale remote-sensing observations. Similarly, modeling output will be produced for a variety of scales, which can be used to address a spectrum of questions and issues from basic science to applications. Making progress toward this priority requires additional research on underlying ecological processes and responses, including identifying climate-related thresholds that could result in discontinuities or abrupt changes in ecosystems and climate-sensitive resources, and the development of models linking geophysical and ecological phenomena. Strategies for implementation include new *in situ* experimental research projects; observations of ecosystems at local, regional, and global scales; synthesis and analysis of diverse ecological data sets, including those from manipulative experiments; and ecological model development and evaluation.

EcoIWG efforts contribute to all five goals described in the *2003 Strategic Plan*, with an emphasis on Goal 4: to "understand the sensitivity and adaptability of different natural and managed ecosystems...to climate and related global changes." EcoIWG activities directly address questions 8.1, 8.2, and 8.3 from the *2003 Strategic Plan*. Synergies and interactions exist with all the other USGCRP research elements (i.e., Atmospheric Composition, Climate Variability and Change, Global Carbon Cycle, Global Water Cycle, Land Use and Land Cover Change, and Human Contributions and Responses).

The agencies participating in the EcoIWG work collaboratively to plan and execute research described in the *2003 Strategic Plan*. Many of the research accomplishments and plans described in this chapter are the outcome of multi-agency efforts. A number of these activities also involve collaborations between the agencies and non-Federal partners. EcoIWG actively engages the larger scientific research community to obtain input to and feedback on its evolving research plans.

HIGHLIGHTS OF RECENT RESEARCH

Climate Impacts on Aquatic Species Management and Conservation.[1,2,3] Research on the effects of climate on aquatic invasive species shows interactions through-

Climate-Induced Changes in Bull Trout Habitat

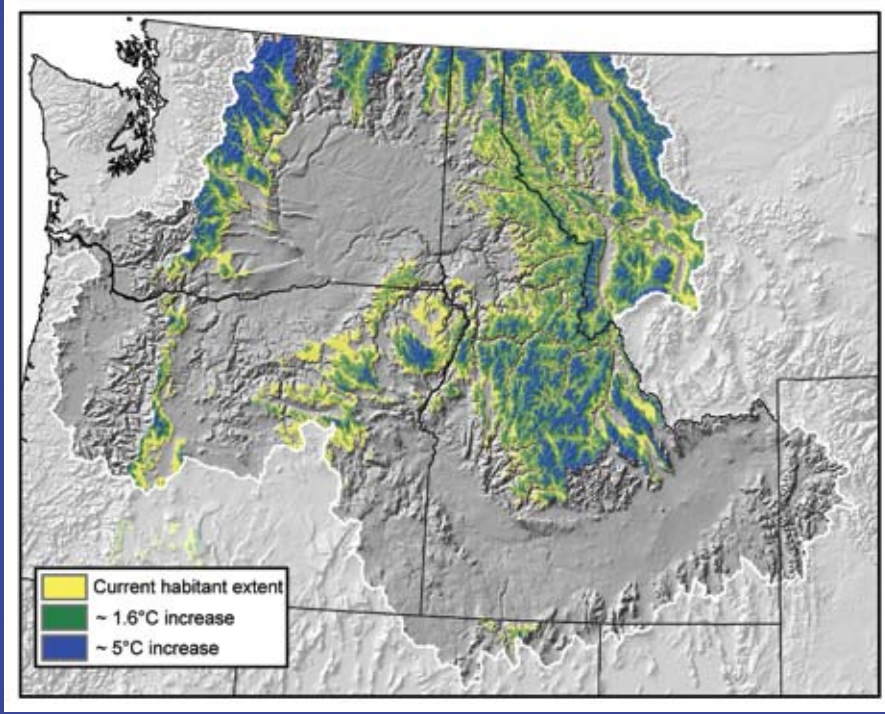

Figure 14: Watersheds with thermally suitable bull trout habitat based on current and future temperature predictions. *Credit B.E. Rieman, D. Isaak, S. Adams, D. Horan, D. Nagel, and C. Luce, U.S. Forest Service, and D. Myers.*

out the invasion pathway. Analyses of climatic effects on invasive aquatic organisms and species of conservation concern suggest potential impacts of changing climate and possible management options. For example, researchers modeled relationships between fish distribution and temperature across the current range of bull trout, an endangered fish species in the Columbia River Basin. Results suggest that projected warming over the next 50 years could decrease reproductive habitat by 18 to 92% and cause even greater losses of large habitat patches critical for population persistence (see Figure 14). These changes also make additional areas susceptible to invasion by the non-native brook trout. Variations in habitat losses and invasive potential across the ranges of native fishes suggest the need for management actions to be prioritized at a regional scale.

Biological Monitoring Data Shows Past Effects and Projects Future Changes.[4,5] Monitoring data from Lake Baikal in central Siberia shows that waters have warmed significantly over the past 60 years (1.21°C since 1946), consequently reorganizing the lake's biotic structure. Chlorophyll *a* has increased by 300% since 1979 and a sentinel zooplankton grazer population by 335% since 1946, with important implications for nutrient cycling and the sustainability of food webs. In the United States, biological monitoring data from Maryland streams were used to project community composition changes and determine sampling power to detect climate change effects. Depending on temperature change scenario and species loss rate assumptions, effects due to climate change may be detected for time horizons as short as 15 years to greater than 100 years. Results from this analysis can inform biological assessment programs to modify activities (e.g., sampling designs) to account for climate change effects and ensure that management goals continue to be met.

Increased Cold Damage to Plants with Warmer Springs?[6] Plant ecologists are concerned that global warming may increase the risk of plant frost damage. The hypothesis is that mild winters and warm springs due to climate change may induce "premature" leaf growth, resulting in exposure of young leaves to subsequent late-spring frosts. The 2007 spring freeze in the eastern United States provided an opportunity to evaluate this hypothesis and assess potential consequences. A warm spring caused early spring leaf growth, followed by a dramatic (and unusual) regional-scale late spring freeze. The freeze resulted in regional-scale leaf damage and death, with extensive defoliation at many locations, observed from the ground and in satellite data. Results indicate that the possibility of future increased fluctuations in spring temperatures pose a threat to some plants in presently temperate climates.

Climate Change and Urban Expansion Isolate Park Ecosystems.[7] Habitat isolation and alteration have implications for ecosystem integrity and biodiversity within parks and protected areas. Urban expansion is reducing the amount and quality of habitat across the Nation and, in the process, isolating parks and protected area habitat as these high-value locations are fragmented by rural residential development. Isolation is particularly problematic in the context of climate change, which is modifying the habitat upon which the wildlife within these increasingly isolated ecosystems depends. Connecting core habitat areas, such as those along the Appalachian Mountain chain (Figure Eco-2), can mitigate some of the climate-induced changes across ecosystems by providing dispersal pathways between suitable habitats necessary to ensure species viability on longer time scales.

High-Elevation Ecosystems May be in Jeopardy Due to Climate Change.[8,9] A study along the northern hardwood-boreal forest ecotone in the Green Mountains of Vermont has shown a shift in forest ecosystems from 1965 to 2005 such that the hardwood forest moved upslope by 91 to 119 m, coinciding with a regional climate warming of 1.1°C. This was a more rapid shift than expected and indicates relatively little time lag in these ecosystems for climatically induced range shifts. In similar research in the Santa Rosa Mountains in southern California, it was observed that the average elevation of dominant plant species increased about 65 m between 1977 and 2007. That upslope shift could not be attributed to changes in air pollution or fire frequency and appeared to be a consequence of warming temperatures, increased precipitation variability, and reduced amount of snow.

Relationships between Historic Climate and Wildfire in the Pacific Northwest.[10] Understanding relationships between past climate and wildfire patterns provides an essential foundation for predicting potential

effects of changing climate on the frequency, extent, and severity of wildfires in the future. A number of models predict increasing fire hazard, particularly in parts of the western United States and in boreal forests, as climate warms. Recent research correlated annual tree-ring fire scar chronologies for 15 ponderosa pine sites in Oregon, Washington, and British Columbia with historical climate patterns from 1651 to 1900. Years with high fire synchrony across all of the sites occurred when spring and

Climate-Induced Changes in Animal Migration

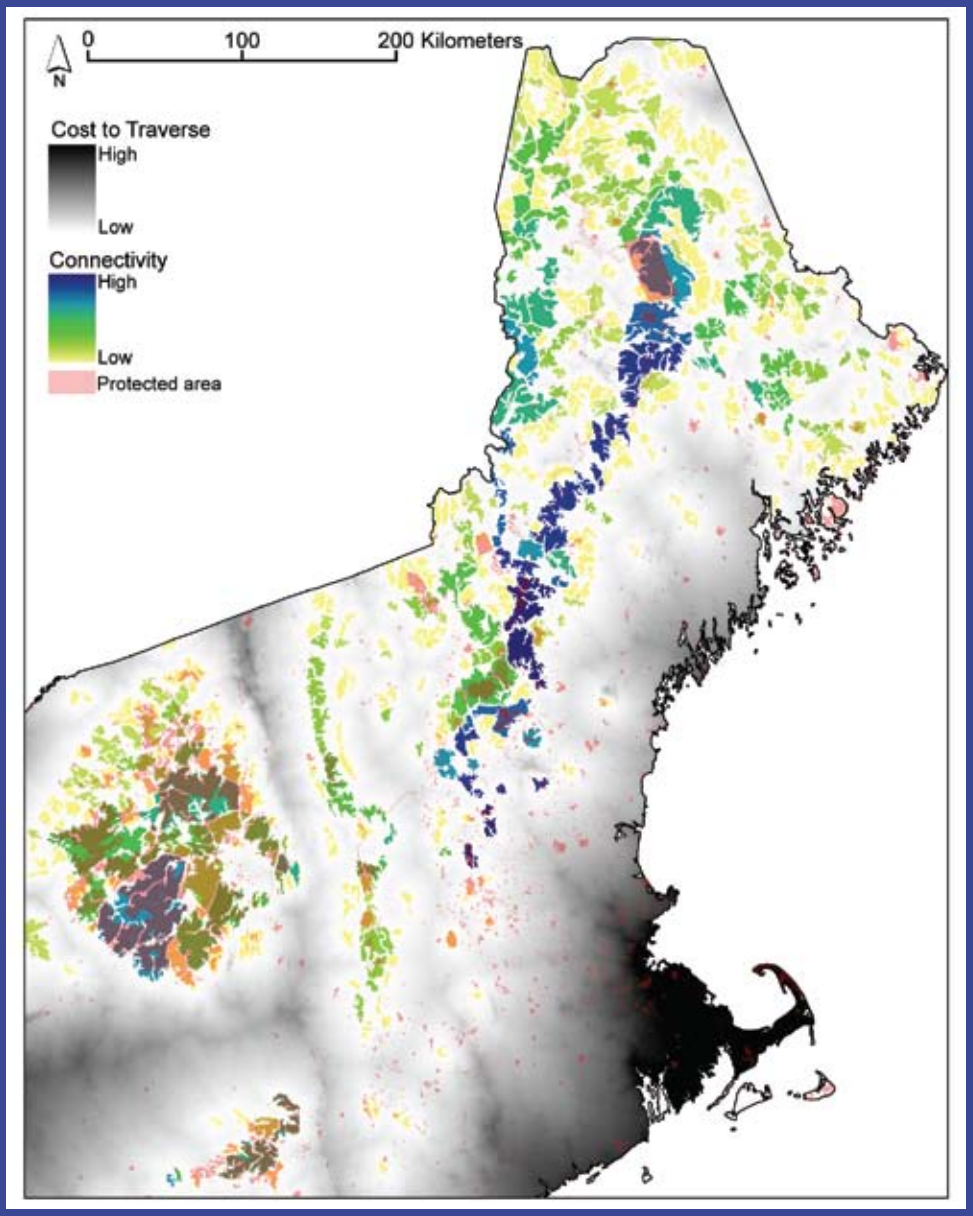

Figure 15: This figure shows habitat areas identified in the northeastern United States using various satellite image data products and the distance from roads and developed areas. The colors correspond to the connectedness of the core habitat areas, where yellows indicate low habitat connectivity and blues indicate high connectivity. A "cost surface" is shown in the background, with lighter shades of gray indicating more permeability of the landscape to animal migration. The high values running through the center of the region indicate a high density of connectivity between high-value habitat areas along the Appalachian Mountain chain. *Credit: S.J. Goetz, P. Jantz, and C.A. Jantz, Woods Hole Research Center (reproduced from* **Remote Sensing of Environment** *with permission from Elsevier).*

summer temperatures were warmer than average and summers were dry. This seasonal climate pattern was associated with warm phases of both the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

Potential Effects of Climate Change on Bird Distribution.[11] To predict potential effects of changing climate on bird species in the northeastern United States, researchers developed models relating current distributions of 150 common bird species to climate, elevation, and vegetation. Using three global climate models, they then studied how distributions might change as climate and habitats shift in the future, with low and high change scenarios for each model. Projected changes were consistent across all scenarios, and suggested the potential for major shifts in ranges and population levels of many bird species. The largest increases in bird species richness were projected for Maine and New Hampshire, and the greatest decreases in the southern part of the study region (Pennsylvania and southern New York). Over 44% of tropical and temperate migrant species were projected to decline, and 33% to increase.

Increased Carbon Dioxide Alters Plant Community Structure in Shortgrass Steppe.[12] A five-year study of the effects of carbon dioxide (CO_2) enrichment on Colorado rangeland, using large open-top chambers, showed that shrubs far outgrew native grasses. The plant biodiversity was largely unchanged, but the plant communities exposed to the ambient versus doubled CO_2 concentrations grew increasingly dissimilar. In particular, *Artemisia frigida* Willd, a common subshrub in North American and Asian grasslands, produced a nearly 40-fold increase in biomass and a 20-fold increase in plant cover with elevated CO_2. This woody encroachment represents a challenge for ranchers and rangeland managers because these shrubs are unsuitable for domestic livestock grazing.

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAPs most relevant to Ecosystems and completed within the period of this report are as follows:

SAP 4.2: Thresholds of Climate Change in Ecosystems (2009)

SAP 4.3: The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity (2008)

SAP 4.4: Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources (2008)

HIGHLIGHTS OF PLANS FOR FY 2010

Testing Analytic Approaches for Determining Climate Sensitivity of Management Practices. A number of different approaches have been taken to determine how to support effective decisionmaking in the context of climate change. These efforts have typically been qualitative and have not attempted to prioritize decisions beyond a coarse, aggregated level. Research will be conducted to evaluate more quantitative approaches to prioritizing decisions and compare them to existing qualitative methods. Research will focus on decisions pertaining to maintaining or enhancing water quality and aquatic ecosystem functioning.

This activity will address Question 8.3 of the 2003 Strategic Plan.

Ecosystem Impacts, Vulnerabilities, and Adaptation Options. Research and integrated assessments will be carried out to determine climate change impacts, identify vulnerabilities, and assess adaptation options in terms of management strategies for several ecosystem types. For example, estuaries are likely to experience severe effects of climate change due to sea level rise, ocean temperature and acidity changes, and coastal erosion and development. Assessment results will assist the National Estuary Program to adapt to the effects of climate change and to implement adaptation strategies. Pilot projects will also be conducted on Experimental Forests and Ranges to develop, test, and refine management strategies and systems that will conserve and enhance resource productivity and health, and address climate change impacts on soil, water, animal habitat, biodiversity, and vegetation composition and structure.

This activity will address Questions 8.2 and 8.3 of the 2003 Strategic Plan.

Experimental Field Study of Warming in Pacific Northwest Prairies. Climatic change will affect the distributions and abundances of plant and animal species, with many of the largest effects likely to be on rare species, species with specialized habitats, and species with relatively constrained geographic ranges. The few remaining high-quality Pacific

Northwest prairies harbor a number of sensitive, rare, and endangered plant species that may be lost with further climatic changes. Research will experimentally examine how warming and changes in summer precipitation might affect the geographic distribution and abundance of prairie plant species, with a particular focus on species with range limits (i.e., cool and warm range "edges") within the region. This research should provide a solid scientific foundation for forecasting effects of climatic change on plant species distributions and persistence in these (and related) ecosystems.

This activity will address Questions 8.2 and 8.3 of the 2003 Strategic Plan.

Discovering Causal Mechanisms of Drought-Induced Pine Mortality in the Southwestern United States. Recent droughts have been associated with widespread mortality in several pine species (including pinyon pine) throughout the southwest. Field experiments are being constructed to uncover the underlying mechanisms of mortality and therefore provide the means to forecast effects of future climatic changes on woodland and forest ecosystems in the southwest. In one particular experiment, large (40 x 40 m) plots of pinyon-juniper woodland in New Mexico are being experimentally manipulated to receive normal precipitation, 50% of normal precipitation, or 150% of normal precipitation. Detailed plant biophysical and physiological measurements will be used to determine whether hydraulic stress in xylem and/or carbon starvation (i.e., the rate of photosynthate use exceeding the rate of photosynthate production) predisposes pine to mortality, including mortality associated with bark beetles.

This activity will address Question 8.2 of the 2003 Strategic Plan.

Forecasting Distribution and Abundance Changes in Ecosystems and Species. A fundamental ecological question is "how will changing climate affect the distribution and numbers of organisms and ecosystems?" Satellite studies typically show changes in patterns at global to landscape/seascape spatial scales and provide the environmental context in which changes in ecosystems and species occur. *In situ* research usually occurs at local to landscape/seascape scales and often focuses on processes. Improving our understanding of and ability to forecast changes in ecosystems and species requires bringing together both approaches to place processes driving changes into their larger contexts. Research will integrate satellite observations and *in situ* measurements within ecological models to forecast changes in the distribution and numbers of aquatic and terrestrial ecosystems and species, information of great importance to resource managers.

This activity will address Questions 8.1, 8.2, and 8.3 of the 2003 Strategic Plan.

Terrestrial Ecosystem Functioning in High Latitudes. Research will be conducted on terrestrial ecosystem functioning in Northern Hemisphere high latitudes that focuses on whole-system responses and feedbacks to global change. These new studies will analyze recent ecosystem changes using remote-sensing data products for North American, circumboreal, or pan-Arctic regions and analyze the impacts of potential ecosystem changes in northern high-latitude systems, including abrupt changes. Studies to advance the scientific basis for new satellite missions that will measure ecosystem three-dimensional structure and ecosystem functional indicators will also be initiated.

This activity will address Questions 8.1 and 8.2 of the 2003 Strategic Plan.

Understanding Ecosystem Connectivity across a Range of Scales.[13] Understanding the relationships between environmental change and ecosystem structure and function at local to regional to continental scales will help scientists predict alterations such as where invasive species are likely to go next. Integrating data from existing and developing networks, such as NSF's Long-Term Ecological Research network and National Ecological Observatory Network, the U.S. Forest Service's Experimental Forests and Ranges, USDA's Agricultural Research Service research stations, and DOE's large-scale climate change

experiments, will lead to an unparalleled level of ecological comparison and forecasting of future changes in response to climatic change.

This activity will address Question 8.2 of the 2003 Strategic Plan.

Sea Level Rise and Coastal Ecosystems. In the Everglades, climate change manifests primarily through sea level rise and hurricane impacts. Sea level rise, coupled with reduced freshwater inflows to Everglades estuaries in the last century, has led to the landward retreat of mangrove wetlands and to hurricane storm surges that spread across this flat landscape. Saltwater intrusion into the shallow Biscayne Aquifer that supplies over six million people with fresh water has also increased. In this context, Everglades restoration projects are seeking ways to increase freshwater flows to the coastal Everglades. However, long-term consequences of climate change due to sea level rise confound the potential outcomes. New research is integrating social and natural science to assess the complex interactions of Everglades restoration, land use changes driven by a growing human population, and water supply issues.

This activity will address Questions 8.2 and 8.3 of the 2003 Strategic Plan.

Climate Change, Land Use Change, and Invasive Species. New research will be conducted on the interacting effects of climate and land use change on terrestrial and aquatic invasive species. These projects will forecast the potential distribution of invasive species under scenarios of future climate and landscape changes, including geographic projections of agricultural weeds and invasive plant species through 2050, and conduct experiments and sampling to create models for managing and predicting incipient invasions and the influence of climate change on gene flow from genetically modified crops and how that may influence the risk of weedy and invasive species. Projects focused on aquatic invasive species will forecast invasion risks in several ecosystems, conduct experiments regarding their interaction with the effects of flood frequency and flood protection, forecast salmonid community changes, and examine facilitation of pathogen invasion.

This activity will address Question 8.2 of the 2003 Strategic Plan.

Modeling Climate-Ecosystem Interactions. None of the basic models used by managers to predict impacts of management activities on vegetation dynamics and other ecosystem processes currently incorporate climate change impacts and interactions. The widely used forest management planning model, FVS (Forest Vegetation Simulator), and other landscape ecosystem dynamics models are being modified to include the impacts of changing climate and atmospheric chemistry on vegetation dynamics and interactions with disturbance processes such as fire, insects, and disease. Continental- or regional-scale models will be modified to improve their capability to assess impacts of climate change and interactions with other stressors such as land use and management, to incorporate ecosystem feedbacks to climate, and to provide user-friendly interfaces.

This activity addresses Questions 8.1 and 8.2 of the 2003 Strategic Plan.

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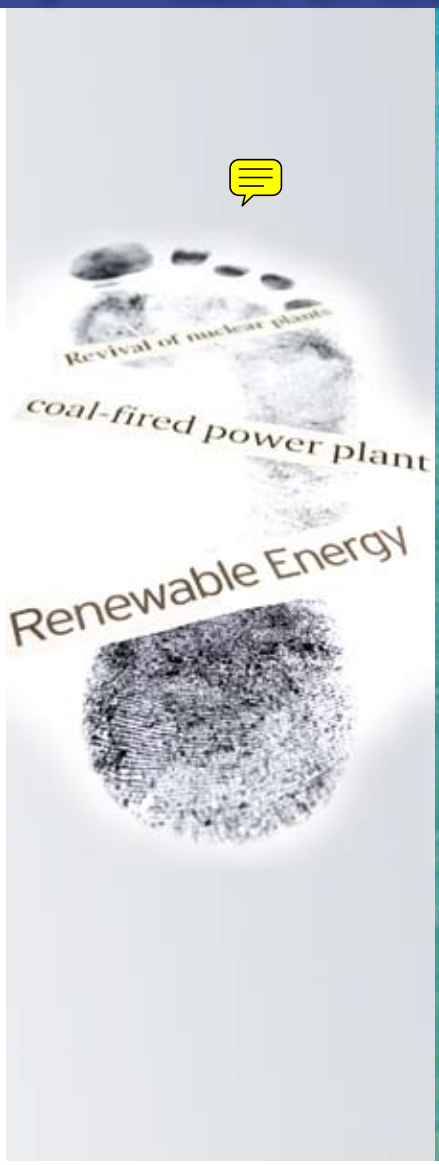
7 HUMAN CONTRIBUTIONS AND RESPONSES TO ENVIRONMENTAL CHANGE



Strategic Research Questions

9.1 What are the magnitudes, interrelationships, and significance of the primary human drivers of, and their potential impact on, global environmental change?

9.2 What are the current and potential future impacts of global environmental variability and change on human welfare, what factors influence the capacity of human societies to respond to change, and how can resilience be increased and vulnerability reduced?

9.3 How can the methods and capabilities for societal decisionmaking under conditions of complexity and uncertainty about global environmental variability and change be enhanced?

9.4 What are the potential human health effects of global environmental change, and what climate, socioeconomic, and environmental information is needed to assess the cumulative risk to health from these effects?

See Chapter 9 of the *2003 Strategic Plan* for detailed discussion of these research questions.

While human activities play a central role in the Earth system and are significant drivers of change in the environment, humans also have the capability to respond to such changes. The systematic analysis of human systems as key drivers of global climate change is central to the development of effective adaptations at all scales: local, regional, national, and global. The National Research Council (NRC) report, *Climate Change Science: An Analysis of Some Key Questions*,[1] concluded that "In order to address the consequences of climate change and better serve the Nation's decision makers, the research enterprise dealing with environmental change and environment-society interactions must be enhanced," and that such an enterprise should include "support of interdisciplinary research that couples physical, chemical, biological, and human systems."

Rapid changes in human societies, brought about by technology, globalization, and an acceleration of the interconnectedness of social, cultural, and economic systems present both methodological and analytical challenges to the analysis of human response to global change. Despite these challenges, attention to how human systems interface with changes in

the global environment is especially important because of its potential to inform public dialogue and promote policies that view human welfare and well-being as inextricably linked with ecosystem integrity. For example, it is well established that human health and well-being is linked to the integrity of environmental conditions, both locally and globally, and that even subtle changes in the natural environment may have dramatic effects on health. Federally supported research has thus far provided information on a broad range of health outcomes likely to be affected by global change, including the adverse effects of ozone, atmospheric pollution, and aeroallergens; ultraviolet (UV) radiation; vector- and water-borne diseases; and heat-related illnesses and mortality. Efforts to anticipate and prepare for these impacts, including the development of enhanced disease surveillance systems, extreme weather early-warning systems, predictive models of disease spread and transmission, and the identification of populations vulnerable to these health effects, will be key components of the public health response to these challenges.

Ideally, human adaptations to global change will serve to enhance the integrity and resilience of both human and natural systems. Toward this goal, a more integrated approach to understanding the complex interactions between human and Earth systems is needed to identify vulnerable components of these systems and pursue options that take advantage of opportunities to enhance resilience.

HIGHLIGHTS OF RECENT RESEARCH

Workshop Series on the Public Health Response to Climate Change. Since January 2007, the Centers for Disease Control and Prevention (CDC) has hosted a series of workshops entitled "The Public Health Response to Climate Change." The workshops in this series were designed to identify gaps and priorities across the environmental and health sectors and to begin the discussion about building a public health response to address the impacts of climate change on human health. During FY 2008, this workshop series included meetings on:

- *Excessive Heat: Confronting Climate Change, Vulnerability, and Urbanization by Improving Heat Health Services, Mitigation Strategies, and Communications*, held November 2007 in Tempe, Arizona
- *The Public Health Response to Climate Change: Effective Health Communication and Marketing*, held January 2008 in Washington, District of Columbia
- *Climate Change and Communities of Color: Assessing and Addressing Vulnerabilities*, held March 2008 in Atlanta, Georgia.
-

Key goals of these workshops included the sharing of information between stakeholder groups, including environmental, public health, academic, advocacy, and nongovernmental organizations (NGOs), in order to strengthen the public health response at the local, State, and Federal level and to enhance the breadth and depth of knowledge about the impacts of climate change on public health.

Climate Change and Aeroallergens. Allergies are prevalent in the United States and impose substantial economic and quality-of-life burdens. A recent nationwide survey reported that over half of the people in the United States test positive for one or more allergens. Climate change, including increased atmospheric carbon dioxide (CO_2) concentrations, could have significant impacts on the production, distribution, dispersion, and allergenicity of aeroallergens and the growth and distribution of organisms that produce them (i.e., weeds, grasses, trees, and fungus). Shifts in aeroallergen production, and subsequent human exposures, may result in

changes in the prevalence and severity of symptoms in individuals with allergenic illnesses. In 2008, a solicitation for competitive research grants was issued seeking proposals that investigate this potential health effect with the intention of awarding multiple grants in 2009.

Capacity Building for Climate Change and Human Health. The Centers for Disease Control and Prevention (CDC) provides external support for climate change and health research relating to epidemiologic and laboratory sciences, infectious disease ecology, modeling and forecasting, climatology and earth science, communication and behavioral-change science. It has also promoted internal workforce development through post-doctoral positions in climate change and health in collaboration with the National Center for Atmospheric Research. In collaboration with the Association of Schools of Public Health (ASPH) additional support is planned for Ph.D.-level dissertation support related to climate change and health, and to build capacity via collaborative grants with local and state-level health departments to support needs assessments and internal training in health impacts of climate change.

Listening Sessions on Climate Change Research. From 2008 to 2009, the USGCRP hosted a series of listening sessions focusing on climate change research interests, informational needs, observations, decision support, communication, and future directions for climate change research. The USGCRP scheduled sessions targeting a variety of sectors at pre-existing professional association scientific meetings, as well as additional, broad-based sessions targeting mixed stakeholders in various geographic regions across the Nation. For example, the Department of Health and Human Services supported a session at the American Public Health Association annual meeting on 29 October 2008 in San Diego, California. This listening session allowed the USGCRP to gather input from public health practitioners and other health professionals from around the Nation regarding the challenges they face in addressing the health impacts of climate change; what additional information, tools, training, and resources they need; and how such resources could best be provided. The session was followed by an additional, broader session that gathered a variety of stakeholders in the southern California region, including representatives from local and State government, resource management agencies, NGOs, academia, and others. The input gathered from these events will be synthesized and used to help shape future directions for the program and climate change research in general. Chapter 10 of this report provides a complete list of the listening sessions with their locations and dates.

Climate Change and Water Quality. The movement of water through the atmosphere, the exchange of water between the atmosphere and the surface, and the movement and storage of water on and below the land surface, are linked through physical and dynamical processes occurring over a variety of spatial and temporal scales. Watershed biogeochemical and other processes, including interaction with human stressors such as changes in land use, pollutant loading, and water flow management, likewise occur over a variety of spatial and temporal scales. The coupling of global climate models with regional-scale climate and hydrology models has the potential to answer a variety of questions on the linkages between climate and water resources. Information regarding the degree and types of impacts on water quality and future demand resulting from a changing climate will be important for water quality management. A solicitation for research proposals on this topic was issued in 2008, with awards to be made in 2009.

Exploring the Role of Science, Technology, and Uncertainty Analysis in Modeling Climate Change Mitigation and Adaptation. A significant challenge for models that simulate human dimensions of climate change is their ability to incorporate the potential role of scientific advances and their implications for transformational shifts in technology to both mitigate and adapt to climate change. Related to this need, on a more general level, improved probabilistic frameworks and uncertainty analysis methods are required that can provide complementary perspectives within and outside of existing integrated assessment models. Meeting these needs requires deeper understanding of the frontiers of energy-related science, as well as understanding the broader sources of uncertainty and their significance. It will probably also require interdisciplinary development of new mathematical and computational methods, building on the strengths of experts in economic modeling, Earth system modeling, energy sciences, mathematical and computational sciences, and more. Accordingly, in July 2008, a workshop was conducted

on uncertainty methods for integrated assessment modeling, with co-sponsorship from DOE's Argonne National Laboratory, the University of Chicago, Northwestern University, and the University of Illinois at Urbana-Champaign. Attended by multiple agency representatives and many leading domestic and international researchers, the workshop encouraged the cross-disciplinary dialog and ideas that will enable progress on these important fronts. Additionally, a major workshop for integrated assessment researchers was conducted in August 2008, with participation by leading scientists in impacts, adaptation, and vulnerability analysis. An initial plan was developed as part of this workshop to more closely connect the research, models, and data between the three communities.

Research into the Energy/Water Nexus. Climate change projections suggest that water availability is likely to be affected in coming decades, especially in regions whose surface water supply depends substantially on winter snowfall. Understanding such changes will have significant implications for the Nation's energy systems, from hydropower resources, cooling water requirements for thermal electricity generation, and water requirements for bioenergy production to energy needs for groundwater pumping and surface water transport, all within the context of demographic, economic, and land use change. There is a need to link improved precipitation modeling capacities in Earth system models with integrated assessment models and analyses of climate change impacts and adaptation potentials in order to anticipate needs for decision support related to possible pressures on the "energy/water nexus." In 2008, competitive research grants were awarded that begin to address these critical intersections and their representations in integrated assessment models.

Understanding Infrastructure and Energy Vulnerabilities under Extreme Weather Challenges. In many cases, social concerns about the effects of climate change are focused on extremes rather than averages. Examples include severe storms, heat waves, and droughts. In addition, there is significant concern that many important ecosystem responses—such as the response of forests and crops to pests, pathogens, and fire—may be quite abrupt, as seen now in the pine bark beetle epidemics in the Pacific Northwest and the increase in fire frequency throughout the western United States The integrated assessment modeling community is developing methods for incorporating our best current understanding of such phenomena in the context of adaptation decisions. In the case of energy systems, particular concerns include effects of heat waves on electricity demand and distribution systems (as in the summer of 2006), effects of droughts on competition among economic sectors for scarce water, and the effects of severe storms on energy infrastructure in vulnerable areas (such as coastal zones). In 2008, competitive research grants were awarded that begin to address these critical research and modeling challenges.

A complete list and description of each of the 21 Synthesis and Assessment Products (SAPs) is given in Chapter 8 of this report. The SAPs most relevant to Human Contributions and Responses and completed within the period of this report are as follows:

SAP 2.1: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Global-Change Scenarios: Their Development and Use (Part B) (2007)

SAP 4.1: Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region (2009)

SAP 4.2: Thresholds of Climate Change in Ecosystems (2009)

SAP 4.3: The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States (2008)
SAP 4.4: Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources (2008)

SAP 4.5: Effects of Climate Change on Energy Production and Use in the United States (2007)

SAP 4.6: Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems (2008)

SAP 4.7: Impacts of Climate Variability and Change on Transportation Systems and Infrastructure - Gulf Coast Study (2008)

HIGHLIGHTS OF PLANS FOR FY 2010

With the increasing need to address the vast research gaps associated with the human dimensions of climate change, the interagency focus of Human Contributions and Responses will be directed at five significant and socially relevant topic areas: urban systems, energy systems, land use change, human health, and water resources. While the group recognizes that these five areas do not cover the entire gamut of human dimensions research needs related to climate change, this approach was chosen to promote advancement through focused effort among the agencies involved with the current Human Contributions and Responses program element.

Climate Change, Air Quality, and Human Health. There is a growing body of scientific evidence that climate change may affect exposures to air pollution. Until recently, air quality and climate change have generally been treated as separate issues. However, they are coupled through many processes (e.g., atmospheric, chemical, radiative)—air pollution can affect climate and climate in turn can affect the sources, chemistry, and transport of air pollutants. Given the spatial distribution of the U.S. population, changes in ambient concentrations and spatial patterns of air pollution will lead to changes (both positive and negative) in exposures and associated health effects. An assessment of these health effects is planned to inform both the public health and air quality management communities.

This activity will address Question 9.4 of the 2003 Strategic Plan

High-Resolution Integrated Assessment Models for Improved Insights into Mitigation and Adaptation. Impacts and potential adaptations are largely defined by the unique circumstances of the local environment and the combination of stressors unique to that location. Additionally, systems can be highly sensitive to temporal shifts in stressors and processes inherent to the system. In some cases, adaptation can happen quickly but in many situations, adaptation requires time or the system is vulnerable and at risk of being overwhelmed, thus failing. Consequently, both spatial and temporal dimensions of climate change are important. Additionally, the temporal and spatial dimensions of human influences on the Earth's climate, such as emissions and land use, are critically important to projections of future climate change. For example, some emissions block solar radiation. Understandably, projections of their potential future geographic distribution and transport are of considerable interest to Earth system modelers. Future land use will greatly affect simulations of the carbon cycle, hydrologic cycle, albedo, and more. Research is planned to explore and improve the spatial and temporal dimensions of integrated assessment models to respond to needs posed by both mitigation and adaptation analyses and decision support. Additionally, future efforts designed to strengthen both Earth system and integrated assessment models will look at the intersection of these two types of models and their combined behaviors at high resolution. Results of a November 2008 long-range planning workshop for the Integrated Assessment Research Program inform these new research directions.

This activity will address Question 9.2 of the 2003 Strategic Plan

Inventory of Impact and Adaptation Research, Programs, and Capabilities. Research efforts are planned to develop two comprehensive databases targeted at climate scientists, modelers, program managers, and decisionmakers. These databases will include two aspects of climate change science that are currently so fragmented that integrated assessment efforts are unable to incorporate them effectively: (a) climate

change impact research and science, and (b) climate change adaptation practices and their benefits, costs, potentials, and limitations. The databases will become a part of an integrated information infrastructure, not only representing existing science but also serving as tools to improve the science by promoting model and tool intercomparisons, supporting discussions of data and analysis standards, and identifying overlaps and possible redundancies in research support across USGCRP agency programs. Preliminary ideas for the design of the databases have been put forward, and will be fully developed during 2009 and 2010. In FY 2009, a working version of the climate change impact research database will be produced and provided to integrated assessment modelers, in consultation with the USGCRP agencies and the impact assessment research community. The climate change adaptation database (which addresses a much larger collection of data) will be elaborated for two key sectors, also in collaboration with relevant agencies, scientists, and networks. In FY 2010, it is expected that the climate change impact database will be completed and made available to the larger climate change science community, and the adaptation database will be expanded to additional sectors, in consultation with individual USGCRP agencies. As appropriate, consideration will be given to approaches to maintaining the databases as the sciences of both impacts and adaptation expand in coming years.

This activity will address Question 9.3 of the 2003 Strategic Plan

Workshops on Climate Change and Public Health. The CDC plans to hold workshops on 'Climate Change and Health in South Asia' with the US-Indo Collaboration on Environmental & Occupational Health, and on 'Climate Change and Local Public Health' in collaboration with the National Association of County and City Health Officials (NACCHO).

This activity will address Question 9.4 of the 2003 Strategic Plan

CHAPTER REFERENCES AND ENDNOTES

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8 DECISION SUPPORT RESOURCES DEVELOPMENT

The Role of Decision Support

Goal 1: Prepare scientific syntheses and assessments to support informed discussion of climate variability and change and associated issues by decisionmakers, stakeholders, the media, and the general public.

Goal 2: Develop resources to support adaptive management and planning for responding to climate variability and climate change, and transition these resources from research to operational application.

Goal 3: Develop and evaluate methods (scenario evaluations, integrated analyses, and alternative analytical approaches) to support climate change policymaking and demonstrate these methods with case studies.

See Chapter 11 of the *2003 Strategic Plan* for detailed discussion of decision support resources development.

One of the main functions of the USGCRP is to provide scientific information for informed decisionmaking through the development of decision support resources. Decision support resources include analyses and assessments, interdisciplinary research, analytical methods (including scenarios and alternative analysis methodologies), model and data product development, communication, and operational services that provide timely and useful information to address questions confronting policymakers, resource managers, and other stakeholders. This research is especially relevant to Goal 5: "Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change."

Decision support resources are targeted at three broad categories of uses: (1) discussion and planning by decisionmakers, stakeholders, the media, and the general public based on state-of-the-science syntheses and assessments; (2) operational adaptive management decisions undertaken by managers of natural resources and built infrastructure (i.e., "climate services applications"); and (3) climate

change policy formulation. Each of these categories has a unique set of stakeholders and requires different decision support tools. However, they share a common reliance on partnerships between scientists and stakeholders to define the problems to be addressed, the nature of decision support resources to be developed, the expected information to be provided, and the approach for describing levels of confidence and key uncertainties.

Development of decision support resources cannot be isolated in a single program element that remains disconnected from research throughout the USGCRP. Responsibility for developing decision support resources is currently distributed across the USGCRP, which has presented certain challenges. Success depends on developing strategies for integrating knowledge from the many diverse fields represented in the program.

HIGHLIGHTS OF RECENT RESEARCH

A primary activity within the USGCRP to meet Decision Support Goal 1 has been the development of 21 Synthesis and Assessment Products (SAPs) focusing on a variety of science and technical issues important for public discussion and decisionmaking. The SAPs are intended to support informed decisionmaking on climate variability and change by a broad group of stakeholders, including policymakers, resource managers, media, and the general public. The development of these SAPs stems from the Global Change Research Act of 1990 (P.L. 101-606, section 106), which directs the program to "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" and to undertake periodic science "assessments."

Table DS-1 gives a complete list of the 21 SAPs, including title, completion date, and brief description. Where each SAP falls within the three broad decisionmaking categories as described in the *2003 Strategic Plan* is identified by title color in the table. Up-to-date information and copies of all SAPs can be obtained from <www.climatescience.gov/Library/sap/sap-summary.php>.

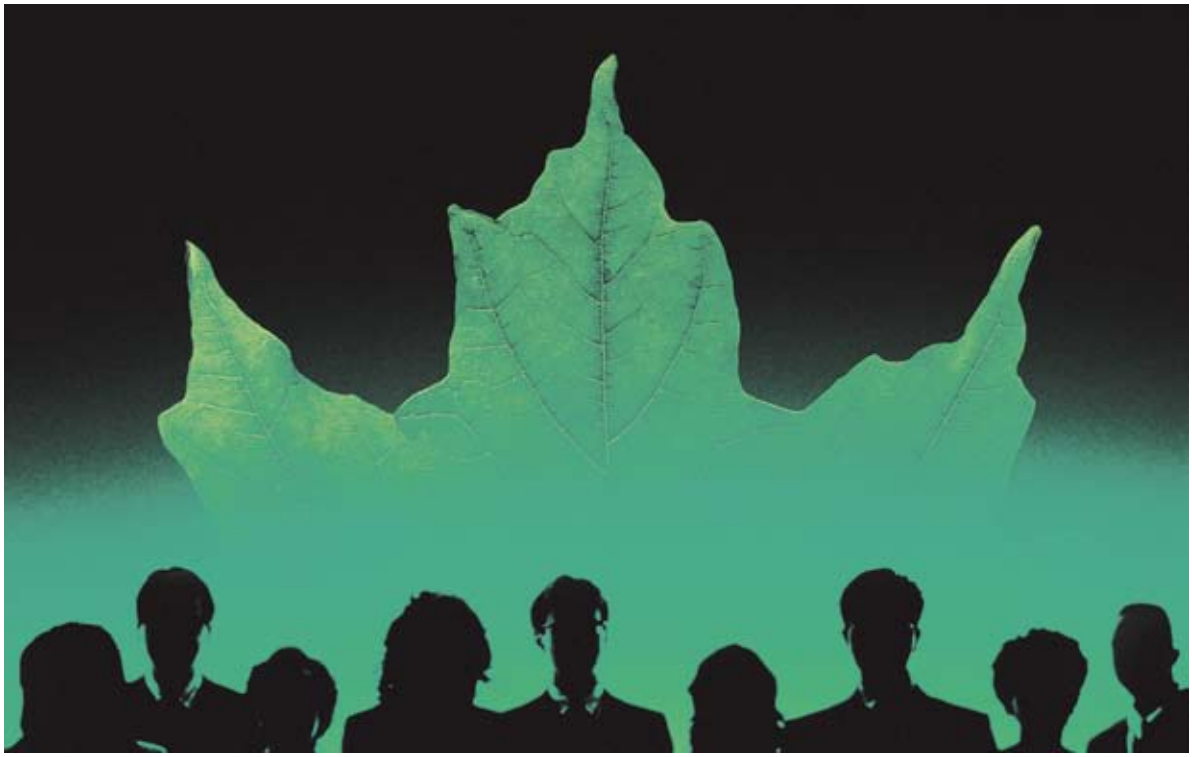

Table DS-1

SYNTHESIS AND ASSESSMENT PRODUCTS	
COLOR KEY FOR CLASSIFICATION OF SAPS BY DECISION SUPPORT PURPOSE To inform evolution of the science research agenda — To inform adaptive management decisions — To inform policy decisions	
Goal 1 - Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.	
1.1	**Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences (2006)** Temperature change is a fundamental measure of climate change. This product addresses temperature changes from the surface through the lower stratosphere and our understanding of the causes of these changes. It assesses progress made since the reports by the National Research Council (2000) and the Intergovernmental Panel on Climate Change (2001) and highlights differences between the individual temperature records determined by components of the existing observational and modeling systems and documents the potential causes of these differences
1.2	**Past Climate Variability and Change in the Arctic and at High Latitudes (2009)** The Arctic and the high latitudes have warmed more rapidly than almost any other region on Earth over at least the last millennium. This warming has been accompanied by a decrease in sea ice cover and thickness and a decrease in ocean salinity. In addition, significant changes in the permafrost active layer are now being detected. The impacts on humans and ecosystems that are associated with these changes were reported in the Arctic Climate Impact Assessment, which was partially funded by USGCRP participating agencies. This SAP focuses on the state of knowledge concerning past changes in the physical climate of this region and the implications of this record of past changes for current and future change. Such information is vital since high-latitude regions are projected to continue to experience the greatest warming in the future.
1.3	**Reanalysis of Historical Climate Data for Key Atmospheric Features (2008)** A reanalysis is a detailed, retrospective study of the state of the atmosphere using a consistent numerical model of the dynamics of the system and based on observations for the time period of the study. This product provides an assessment of the capability and limitations of state-of-the-art climate reanalysis to describe past and current climate conditions, and the consequent implications for scientifically interpreting the causes of climate variations and change. The product summarizes the present status of national and international climate reanalysis efforts, and discusses key research findings on the strengths and limitations of current reanalysis products for describing and analyzing the causes of climate variations and trends that have occurred during the time period of the reanalysis records (roughly the past half-century). The report describes how reanalysis products have been used in documenting, integrating, and advancing our knowledge of climate system behavior, as well as in ascertaining significant remaining uncertainties in descriptions and physical understanding of the climate system.
Goal 2 - Improve quantification of the forces bringing about changes in the Earth's climate and related systems	
2.1	**Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Global-Change Scenarios: Their Development and Use (Part B) (2007)** This product provides a new long-term, global reference for greenhouse gas stabilization scenarios and an evaluation of the process by which scenarios are developed and used. SAP 2.1 consists of two parts. Part A uses computer-based scenarios to evaluate four alternative stabilization levels of greenhouse gases in the atmosphere and the implications for energy and the economy of achieving each level. Part A includes stabilization scenarios for the six primary anthropogenic greenhouse gases—carbon dioxide, nitrous oxide, methane, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride—and it uses updated economic and technological data and new tools for scenario development. Although these scenarios should not be considered definitive predictions of future events, they provide valuable insights for decisionmakers. Part B examines how scenarios have been developed and used in global climate change applications, evaluates the effectiveness of current scenarios, and recommends ways to make future scenarios more useful. Part B of the report concludes that scenarios can support decisionmaking by providing insights regarding key uncertainties, including future emissions and climate as well as other environmental and economic conditions.

2.2	**The First State of the Carbon Cycle Report (SOCCR) rth American Carbon Budget and Implications for the Global Carbon Cycle (2007)** This product provides a synthesis and integration of the current knowledge of the North American carbon budget (including land, atmosphere, inland waters, and adjacent oceans) and its context within the global carbon cycle. In a format useful to decisionmakers, it summarizes our knowledge of carbon cycle properties and changes relevant to the contributions of, and impacts upon, the United States and the rest of the world; and provides scientific information for U.S. decision support focused on key issues for carbon management and policy. It addresses carbon emissions; natural reservoirs and sequestration; rates of transfer; the consequences of changes in carbon cycling; effects of purposeful carbon management; effects of agriculture, forestry, and natural resource management; and socioeconomic drivers and consequences. The report includes an analysis of North America's carbon budget that documents the state of knowledge and quantifies uncertainties.
2.3	**Aerosol Properties and Their Impacts on Climate (2009)** Aerosols can cause a net cooling or warming within the climate system, depending upon their physical and chemical characteristics. In addition to these direct effects, aerosols can also have indirect effects on radiative forcing of the climate system by changing cloud properties. The first phase of development of this product was to produce major scientific reviews of the following three topics: dependence of radiative forcing by tropospheric aerosols on aerosol composition in the North Atlantic, Pacific, and Indian Ocean regions; measurement-based understanding of aerosol radiative forcing from remote-sensing observations; and model intercomparison to quantify uncertainties associated with indirect aerosol forcing. The second-phase product draws upon the scientific information gathered by the development of the Intergovernmental Panel on Climate Change Fourth Assessment Report and the National Research Council review, Radiative Forcing of Climate Change.
2.4	**Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications ( )** Measurements of ozone-depleting gases in the atmosphere have shown that the concentrations of these gases are declining in response to the agreements reached under the Montreal Protocol. This report provides an update on trends in stratospheric ozone, ozone-depleting gases, and ultraviolet radiation exposure and on progress in improving model evaluations of the sensitivity of the ozone layer to changes in atmospheric composition and climate, with a particular emphasis on newly synthesized information regarding the role of and implications for the United States. Such information is key to ensuring that international agreements to phase out production of ozone-depleting substances are having the expected outcome: recovery of the protective ozone layer. The report derives most of its information from recent international assessments of stratospheric ozone, ozone-depleting substances, and climate.
Goal 3 - Reduce uncertainty in projections of how the Earth's climate and environmental systems may change in the future	
3.1	**Climate Models: An Assessment of Strengths and Limitations for User Application 8)** The topics addressed by this product are the strengths and limitations of climate models at different spatial and temporal scales. Its purpose is to provide information on the results from climate models in ways that will allow the potential user of the information to evaluate how best it may be applied. The product focuses on natural and human-caused factors influencing climate variability and change during the period from 1870 to 2000. It characterizes sources of uncertainty in climate models and their implications for estimating future climate change. This product will be limited to the models and their sensitivity, feedbacks, strengths, and limitations, rather than making specific projections of the future.
3.2	**Climate Projections for Research and Assessment Based on CCTP Emissions Scenarios (8)** This product has two distinct components. The first is to produce climate projections for research and assessment based on scenarios of greenhouse gas emissions and atmospheric concentrations as reported in SAP 2.1a. The second is to assess the future climate impacts of short-lived gaseous and particulate species.

3.3	**Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands (2008)** The impact of climate extremes can be severe and wide-ranging. There is evidence that the economic impact of weather and climate extremes in the United States has increased over the past several decades, but the evidence for increases in extreme weather and climate events varies depending on the event of interest. These events may be related to temperature parameters (severe freezes, heat waves), precipitation (wet spells, heavy precipitation events, droughts, ice and hail, and snow cover and depth), or tropical and extratropical storm frequency. The report focused on identifying recent changes and trends in such parameters, as well as identifying what can be said about future changes. Since extreme weather and climate events on a global scale are regularly addressed in international assessments, this SAP focuses on weather and climate extremes primarily across Canada, Mexico, and the United States.
3.4	**Risks of Abrupt Changes in Global Climate (2008)** The paleoclimate record reveals that Earth's climate can change rapidly and strongly between different stable states. Various scenarios portray future abrupt climate change large enough to pose a significant challenge to society. The goal of this product was to review and synthesize current understanding of abrupt climate change and to identify gaps in knowledge. The report integrates information from the paleoclimate record, the instrumental record, and numerical model-based studies at various spatial scales. Key identified risks, such as changes in ocean thermohaline circulation and alteration of terrestrial hydrologic conditions (e.g., the location or amount of precipitation), received special attention because the potential impacts on society are significant.
Goal 4 - Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes	
4.1	**Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region (2009)** This product examines the vulnerability of coastal areas in the U.S. Mid-Atlantic States to sea level change. Specific questions addressed include identifying which areas are low enough to be inundated by tides, how floodplains would change due to a changing climate, which areas might be subject to erosion, and locations where wetlands will be able to migrate inland versus locations where shores will be protected. The product examines the implications of sea level rise, including impacts on population and economic activity in vulnerable areas, costs of shore protection, ecological effects, flood damages, public access to modified shore areas, cases where sea level rise justifies policy changes, options being considered by conservancies and governments, and lessons from the unfolding consequences of the 2005 hurricanes in the Gulf Coast region.
4.2	**Thresholds of Climate Change in Ecosystems (2009)** This SAP defines "ecological threshold" as "the point at which there is an abrupt change in an ecosystem quality, property, or phenomenon, or where small changes in one or more external conditions produce large and persistent responses in an ecosystem." Ecological thresholds occur when external factors, positive feedbacks, or nonlinear instabilities in a system cause changes to propagate in a domino-like fashion that is potentially irreversible. This report reviews threshold changes in North American ecosystems that could be induced by climatic change and addresses the significant challenges these threshold crossings impose on resource and land managers. Sudden changes in ecosystems and the goods and services they provide are not well understood, but they are extremely important to successful development of adaptation strategies by natural resource managers in a changing world. The report provides an overview of what is known about ecological thresholds and where they are likely to occur and presents key examples of climate-induced threshold changes. It also identifies those areas where research is most needed to improve knowledge and understand the uncertainties. The report suggests a suite of potential actions that land and resource managers could use to improve the likelihood of successful adaptation for the resources they manage, even under conditions of incomplete understanding of what drives thresholds of change and when changes will occur. This synthesis effort identified a suite of potential actions that, taken together or separately, can begin to improve the understanding of thresholds and increase the likelihood of success in developing management and adaptation strategies in a changing climate, before, during, and after thresholds are crossed. In general, it is essential to increase the resilience of ecosystems and thus to slow or prevent the crossing of thresholds; to identify early warning signals of impending threshold changes; and to employ adaptive management strategies to deal with new conditions, new successional trajectories, and new combinations of species.

4.3	**The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States (2008)** This report addresses the effects of climate change on agriculture, forestry, land and water resources, and biodiversity. Air and water temperature, precipitation, and related climate variables are fundamental regulators of biological processes. For this reason, human-induced climate change has the potential to affect the condition, composition, structure, and function of ecosystems. Such changes may also alter the linkages and feedbacks between ecosystems and the climate system. Additionally, ecosystems produce a wide array of goods and services valued by humans and in many cases essential for human survival and well being. Therefore, climate-related changes in ecosystems and other key resources could have impacts on human communities and economic conditions.
4.4	**Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources (2008)** Strategies for protecting climate-sensitive ecosystems will be increasingly important for management, because impacts resulting from a changing climate system are already evident and will persist into the future. Adaptation options for enhancing ecosystem resilience include changes in management processes, practices, or structures to reduce anticipated damages or enhance beneficial responses associated with climate variability and change. Many existing best management practices for "traditional" stressors of concern have the added benefit of reducing climate change exacerbations of those stressors, although this may require adjustments in the timing and placement of management practices. For example, assessments of selected federally protected lands identify specific adaptation approaches to increase ecosystem resilience: protecting key ecosystem features; reducing other anthropogenic stresses; representation; replication; restoration; refugia; and relocation. Success of these strategies will depend on recognizing the barriers to implementing new strategies, expanding collaboration among ecosystem managers, creatively re-examining program goals and authorities, and being flexible in setting priorities and managing for change.
4.5	**Effects of Global Change on Energy Production and Use in the United States (2007)** This report summarizes current knowledge of the potential effects of climatic change on energy production and use in the United States. It focuses on three questions: (1) how might climatic change affect energy use in the United States, (2) how might climatic change affect energy production and supply in the United States, and (3) how might climatic change have other effects that indirectly shape energy production and use in the United States? Great care was taken in answering these questions, for two reasons. One, the available research literature on these key questions is limited, supporting a discussion of the issues but not providing definite answers. Two, as with many other aspects of the potential effects of climatic change on the United States, the effects on energy production and use depend on more than climatic change alone; other potentially important factors include patterns of economic growth and land use, patterns of population growth and distribution, technological change, and social and cultural trends that could shape policies and actions, individually and institutionally.
4.6	Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems (2008) This product examines the effects of global change on human systems. The impacts of climate variability, climate change, shifting patterns of land use, and changes in population patterns are human problems, not simply problems for the natural or the physical world. This SAP examines the vulnerability of human health and socioeconomic systems to global environmental change across three areas of potential impacts and adaptations: human health, human settlements, and human welfare. It addresses the questions of what, where, and when climate variability and change will affect U.S. social systems. The challenge for this project was to assess risks associated with health, welfare, and settlements and to identify and develop timely adaptive strategies to address human vulnerabilities. The primary goals for adaptation to climate change and variability focus on managing significant risks proactively when possible; establishing protocols to detect and measure risks; and leveraging technical and institutional adaptive capacity to address new climate risks, especially as they exceed conventional adaptive measures.
4.7	**Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study (2008)** This product addresses the potential effects of climate variability and change on transportation infrastructure and systems in the central Gulf Coast of the United States. The purpose of this study was to increase the knowledge base regarding the risks and sensitivities of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that may be considered to ensure a robust and reliable transportation network. Implications for all transportation modes—surface, marine, and aviation—are addressed. The three-phase study focuses on the Gulf Coast, and assesses the significant risks to transportation, develops methodologies to be applied in other geographic locations, identifies potential strategies for adaptation, and develops decision support tools to assist transportation decisionmakers in incorporating climate-related trend information into transportation system planning, design, engineering, and operational decisions.

Goal 5 - Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change	
5.1	**Uses and Limitations of Observations, Data, Forecasts, and Other Projections (20**  This product focuses on characterizing a subset of the observations from remote sensing and in situ instrumentation that are of high value for decisionmaking. The product characterizes observational capabilities that are currently or could be used in decision support tools, catalogs a subset of ongoing decision support activities that use these capabilities, and evaluates a limited number of case studies of these decision support activities. The detailed evaluation of decision support activities and demonstration projects provides information to agencies and organizations responsible for developing, operating, and maintaining selected decision support processes and tools. The evaluation also provides information on the nature of interactions between users and producers of climate science information, approaches for accessing science information, and assimilation of scientific information in the decisionmaking process. The product includes an online catalog of decision support demonstration projects with interactive links, which will be updated as additional experiments are conducted and new approaches to incorporating and benchmarking application of observations and other global change research products evolve.
5.2	**Best Practice Approaches for Scie**  **Uncertainty in Decisionmaking (2009)** This product addresses the issue of uncertainty and its relationship to science, assessment, and decisionmaking. Specifically, the product is intended to help improve the quality and consistency of information about scientific uncertainty presented to decisionmakers and other users of USGCRP reports by identifying “best practice” options recommended in the literature on this subject; to improve communication between scientists and users of the products by providing recommendations for addressing uncertainty; and to provide a brief overview of the literature on approaches for communicating and considering uncertainty related to climate.
5.3	**Decision Support Experiments and Evaluations (20**  This product concentrates on the water resource management sector. It describes and evaluates current forecasts, assesses how forecasts are being used in decision settings, and evaluates decisionmakers’ level of confidence in these forecasts. The participants in the development of this product (primarily consisting of government officials, researchers, and users) evaluated forecasts as well as their delivery in order to identify options for improving partnerships between the research and user communities. The product informs decisionmakers about the experiences of others who have experimented with the use of seasonal and interannual forecasts and other observational data; climatologists and social scientists about how to advance the delivery of decision support resources that use the most recent forecast products, methodologies, and tools; and science managers as they plan for future investments in research related to forecasts and their role in decision support.

National Research Council Study: Informing Decisions in a Changing Climate. In March 2009, the National Research Council (NRC) Panel on Strategies and Methods for Climate-Related Decision Support, under the Committee on the Human Dimensions of Global Change, released a report entitled *Informing Decisions in a Changing Climate*. The report found that "climate change poses challenges not only for the many decision makers it will affect, but also for Federal agencies and for the scientific community." Decision support, defined in the report as organized efforts to produce, disseminate, and facilitate the use of data and information in order to improve the quality and efficacy of climate-related decisions, is an essential component of a successful response strategy to climate change. The report laid out nine recommendations to serve as core principles characterizing effective climate change decision support:

1. Government agencies and other organizations, including the scientific community, should organize their decision support efforts around six principles of effective decision support: (i) begin with users' needs; (ii) give higher priority to processes over products; (iii) link information producers and users; (iv) build connections across disciplines and organizations; (v) seek institutional stability; and (vi) design processes for learning.
2. Federal agencies should develop or expand decision support systems needed by the climate-affected regions, sectors, and constituencies they serve.
3. Federal agencies in their own decision support activities and in fostering decision support by others should use the approach of deliberation with analysis when feasible. This is the process most likely to encourage the emergence of good climate-related decisions over time. The Federal Government should fund research focused on decision support efforts that combine deliberation with analysis and that use other appropriate learning models, with the aim of improving decision support for a changing climate.
4. Federal agencies and other entities that provide decision support should monitor changes in science, policy, and climate-related events, including changes outside the United States, that are likely to alter the demand and opportunities for effective decision support.
5. Federal agencies should promote learning by supporting decision support networks to share lessons and technical capabilities.
6. The Federal agencies that manage research activities mandated under the U.S. Global Change Research Act (USGCRA) should organize a program of research for informing climate change response as a component of equal importance to the current national program of research on climate change processes. This program should include research *for* and *on* decision support, aimed at providing decision-relevant knowledge and information for climate responses.
7. The Federal Government should expand and maintain national observational systems to provide information needed for climate decision support. These systems should link existing data on physical, ecological, social, economic, and health variables relevant to climate decisions to each other and develop new data and key indicators as needed. The effort should be informed by dialogues among potential producers and users of the indicators at different levels of analysis and action and should be coordinated with efforts in other parts of the world to provide a stronger global basis for research and decision support.
8. The Federal Government should recognize the need for scientists with specialized knowledge in societal issues and the science of decision support in the field of climate change response. There should be expanded federal support to enable students and scientists to build their capacity as researchers and advisers to decision makers who are dealing with climate change.
9. The Federal Government should undertake a national initiative for climate-related decision support under the mandate of the USGCRA and other existing legal authority. This initiative should include a service element to support and catalyze processes to inform climate-related decisions and a research element to develop the science of climate response to inform climate-related decisions and to promote systematic improvement of decision support processes and products in all relevant sectors of U.S. society and around the world.

This report and the NRC's report, *Restructuring Federal Climate Change Research to Meet the Challenges*

of Climate Change (summarized in the introductory chapter), both call for "significant change in research activities being conducted under the authority of the USGCRA, including [expanding] underdeveloped areas of research and finding appropriate organizational homes for research that is now not being done."

Natural Resource Management Ad Hoc Interagency Work Group. The USGCRP and the OSTP have co-sponsored two information-gathering meetings with resource management and regulatory agency representatives from across the Federal Government. The meetings were designed to gather input on the climate information needs of end users in various resource management roles and identify the gaps between the needs of information resource managers and the information currently being provided by climate change scientists. The discussions clearly highlighted the need to develop a mechanism for a two-way dialog between researchers and end users of climate information to ensure that the end users' needs are met in any future development of climate services. A desire to create an ad hoc working group of natural resource managers within the USGCRP emerged during the meetings. The ultimate goal of establishing this ad hoc interagency working group is to create a mechanism by which the program can reach out to the end-user community at the Federal level. This two-way communication will inform the program and ultimately climate change research efforts so that the outcomes and end products are useful to those making decisions regarding climate change.

National Security and Climate Change Workshop. To support another end-user community, the USGCRP hosted a daylong workshop for approximately 30 participants from multiple agencies, representing both the climate science and national security/intelligence communities. In preparation for this workshop, the program office created a workshop planning committee of six professionals from various agencies and organizations that met in person, as well as via phone and electronic communication. With the help of this group, USGCRP staff identified and invited specific stakeholders to participate in this event. Input received and resources shared during this workshop will be used to help identify additional gaps in connecting the climate science and national security/intelligence communities when addressing climate change impacts. The USGCRP also served as the liaison for workshop presenters and as official rapporteur, developing the workshop summary report, which highlights key strengths, challenges, and options for moving forward, and disseminating it to all participants. As a result of this workshop, the intelligence community will develop and provide a report on the integrated climate science needs of that community. The report will be shared with the USGCRP agencies and the broader climate science community. The USGCRP will continue to exchange information with participants in this workshop, and initiate additional events that will help focus more on meeting the climate science needs of this end-user community.

Listening Sessions to Gather Stakeholder Input on Federal Climate Science.[1] Beginning in the fall of 2007 and continuing into the present, the USGCRP has hosted a series of "listening sessions" that target specific geographic regions and disciplinary sectors (see Table DS-2). Some listening sessions are organized as stand-alone events, while others are held in conjunction with established meetings or conferences. At each session, representatives from the program provide a brief overview of USGCRP activities, including those most relevant for the region or sector of focus, and then ask participants to discuss their interests and activities, information needs, and expectations for the future directions of climate change research, observations, decision support, and communication. The input from each session is collected into a report, available from the USGCRP web site, and contributes to the USGCRP's ongoing strategic planning process.

Carbon Management and Decision Support

Carbon cycle research provides scientific information to decisionmakers that enables better carbon management and climate change mitigation decisions. The research informs agricultural and forest managers about sequestration, alternative fuels, and inventories, and the impact of this research on management strategies is expected to increase over the course of this program.

Conversion of Tropical Forests to Savanna.[2] An international research team studying interactions among forest logging, agro industrial expansion, climate, and fire in causing conversion from forest to non-

Table DS-2. Listening Sessions

Listening Session	Location	Date
CCSP Workshop on the Scientific Assessment of Ozone Depletion (2006)	Silver Spring, MD	July 2007
Climate Information Users Roundtable	Washington, DC	October 2007
Western Water Managers Roundtable	Boulder, CO	March 2008
American Geophysical Union Joint Assembly Meeting Listening Session	Fort Lauderdale, FL	May 2008
Pacific Climate Information System Steering Committee and Working Group Listening Session	Honolulu, HI	August 2008
Corn and Climate Workshop Listening Session	Ames, IA	September 2008
Climate Professionals Roundtable	Washington, DC	October 2008
Central New York Regional Listening Session	Syracuse, NY	October 2008
Partnership for Air Transportation Noise and Emissions Reduction Listening Session	Chicago, IL	October 2008
Alaska Tribal Conference on Environmental Management Listening Session	Anchorage, AK	October 2008
Southern California Regional Listening Session	La Jolla, CA	October 2008
American Public Health Association Annual Meeting Listening Session	San Diego, CA	October 2008
A Conference on Ecosystem Services Listening Session	Naples, FL	December 2008
American Geophysical Society Fall Meeting Listening Session	San Francisco, CA	December 2008
American Meteorological Society Annual Meeting Listening Session	Phoenix, AZ	January 2009
Arizona Regional Listening Session	Tempe, AZ	January 2009
Transportation Research Board Annual Meeting Listening Session	Washington, DC	January 2009
Association of Metropolitan Water Agencies Water Policy Conference / American Water Works Association Listening Session	Washington, DC	April 2009

forest is providing new insights into the complex socioeconomic controls on the carbon balance of the region and on climate. By integrating field results with models of the different components of the system, the project shows how these factors interplay and determine land use and carbon emissions. An analysis of current environmental legislation and planned new forest reserves indicates that these actions could significantly reduce carbon emissions resulting from conversion of forests to savanna that otherwise would exacerbate global warming.

Soil Carbon Content Affected by Agricultural Management Practices.[3,4,5] Soil carbon quality and quantity were studied on private and managed lands that have been farmed under a range of agricultural management practices for various periods of time. After observations and synthesis, the analysis demonstrates that both the quantity and quality of soil carbon is enhanced under no-till and diversified crop rotations. Further, carbon sequestration over several years of organic crop rotations was found to be greater than that of a conventional tillage system by 10 to 19%, and was greater than a no-till system by

3 to 11%. The results offer insights into management practices that can be used to sequester carbon for soil quality improvements and to mitigate increases in atmospheric greenhouse gas concentrations.

An Assessment of Climate Information for Watershed Management Associated with Wildfire in the Western United States.[6] The use of climate forecast information in fire management began because decisionmakers within the wildland fire management community were open to new information, due to legal challenges, public pressure, and a "landmark" wildfire season in 2000. The National Fire Plan (2000) and its associated 10-year Comprehensive Strategy reflected an increased receptiveness for new ways of coping with vulnerabilities; it called for a community-based approach to reducing wildland fires that is proactive and collaborative. Improvements in climate forecasting, and research on interactions between climate and wildland fire occurrence, have generated opportunities for improving the use of seasonal climate forecasts by fire managers. This finding was one of the case studies as part of SAP 5.3, *Decision Support Experiments and Evaluations using Seasonal-to-Interannual Forecasts and Observational Data: A Focus on Water Resources.* The study found that fire managers could now better anticipate annual fire risk, including potential damage to watersheds over the course of the year. Climate information can help managers plan for fire risk in the context of watershed management and post-fire impacts, including impacts on water resources. One danger is inundation of water storage and treatment facilities with sediment-rich water, creating the potential for significant expense for pre-treatment of water or for facilities repair. Post-fire runoff can also raise nitrate concentrations to levels that exceed the Federal drinking water standard. Mudslides and soil stability are also a concern after wildland fire. The project, initiated in 2000, continues to produce annual fire-climate outlooks. The interactions between climate scientists and fire managers clearly demonstrated the utility of climate information for managing watershed problems associated with wildfire. Climate forecast information in fire management is now part of accepted practice by agencies, and has produced spin-off activities managed and sustained by the agencies and new participants.

Highlights of Plans for FY 2010

In response to the NRC reports mentioned above, the program is considering restructuring decision support efforts to enhance overall effectiveness. Future plans include structuring decision support research efforts on the science for decision support, science of decision support, and making decision support operational. The program will identify and implement a scoping group of agency representatives knowledgeable about the field of decision support. This group will examine potential options for future decision support research and activities within the program.

Current decision support efforts planned by or underway in particular program elements will continue to move forward during this transition to a stronger, more focused decision support element. Examples include Carbon Management, Post-Wildfire Watershed Management, and Decision Support. Projects that are currently underway will allow Federal agencies, industries, and private landowners to include scientific observations, ecosystem models, and online tools (products of carbon cycle science research) in resource management and decision policies. These projects are presently having a particular impact on forest and agricultural management, as described below.

Carbon Stabilization in Soils and Crops. Projects currently underway will focus on thresholds for carbon stabilization in soils and crops, estimates of recalcitrant carbon stocks in soils, especially black carbon, assessing the impacts of fire and insect disturbance on terrestrial carbon budgets, and effects of management and biofuels production on carbon balance and sustainable production. Planned requests for applications will include decision support and promote networking for a broader synthesis of carbon stocks and vulnerabilities.

Agriculture Systems and Emissions of Greenhouse Gases. A decision support system for management of greenhouse gas emissions from agricultural cropping systems is nearing completion using greenhouse gas emission data from the nationwide Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet). A database of greenhouse gas emissions from selected crop, pasture, and rangeland systems in the United States studied by GRACEnet will be made publicly available. Remote-sensing technologies for mapping crop cover and crop management practices that affect soil conservation and soil carbon will be advanced and evaluated.

Monitoring Soil Resources in Agricultural Lands. Increasing pressure on soil resources in combination with the need to understand how these resources are responding to changing climate has led to the development of a national soil-monitoring network. The monitoring network is currently evaluating soil carbon stock trends in the upper Midwest using a combination of soil sampling, satellite remote-sensing data, and modeling. The results will inform policymakers about carbon sources and sinks in agricultural regions, and form a basis for projections of the greenhouse gas mitigation potential of carbon management practices. The monitoring network of the National Resources Inventory has provided long-term monitoring of land use and management activity since the early 1980s. The network will continue to provide invaluable information to evaluate the influence of climate forcing and management activity on soil resources and ensure long-term sustainability of agricultural production.

CHAPTER REFERENCES AND ENDNOTES

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9 OBSERVING AND MONITORING THE CLIMATE SYSTEM

Observing and Monitoring the Climate System

Goal 12.1: Design, develop, deploy, and integrate observation components into a comprehensive system.
Goal 12.2: Accelerate the development and deployment of observing and monitoring elements needed for decision support.
Goal 12.3: Provide stewardship of the observing system.
Goal 12.4: Integrate modeling activities with the observing system.
Goal 12.5: Foster international cooperation to develop a complete global observing system.
Goal 12.6: Manage the observing system with an effective interagency structure.

Data and Information Management

Goal 13.1: Collect and manage data in multiple locations.
Goal 13.2: Enable users to discover and access data and information via the Internet.
Goal 13.3: Develop integrated information data products for scientists and decisionmakers.
Goal 13.4: Preserve data and information.

See Chapters 12 and 13 of the *2003 Strategic Plan* for detailed discussion of these goals.

Two overarching questions are identified in the *2003 Strategic Plan* for "Observing and Monitoring the Climate System" (Chapter 12) and "Data Management and Information" (Chapter 13). These questions continue to offer guidance to these elements of the program:

- How can we provide active stewardship for an observation system that will document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society?
- How can we provide seamless, platform-independent, timely, and open access to integrated data, products, information, and tools with sufficient accuracy and precision to address climate and associated global changes?

High-quality, long-term observations of the global environment are essential for defining the current state of the Earth's environmental system, its history, and its variability. This task requires both space- and surface-based observation systems. Climate observations encompass a broad range of environmental observations, including

(1) routine weather observations, which are collected consistently over a long period of time; (2) observations collected as part of research investigations to elucidate processes that contribute to maintaining climate patterns or their variability; (3) highly precise, continuous observations of climate system variables collected for the express purpose of documenting long-term (decadal to centennial) change; and (4) observations of climate proxies, collected to extend the instrumental climate record to remote regions and back in time.

The United States contributes to the development and operation of several global observing systems, both research and operational, that collectively provide a comprehensive measure of climate system variability and climate change processes. These systems are a baseline Earth-observing system and include NASA, NOAA, and USGS Earth-observing satellites and extensive *in situ* observational capabilities. The USGCRP also supports several ground-based measurement activities that provide the data used in studies of the various climate processes necessary for better understanding of climate change. U.S. observational and monitoring activities contribute significantly to several international observing systems, including the Global Climate Observing System (GCOS) principally sponsored by the World Meteorological Organization (WMO); the Global Ocean Observing System sponsored by the United Nations Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission (IOC); and the Global Terrestrial Observing System sponsored by the United Nations Food and Agriculture Organization. The latter two have climate-related elements being developed jointly with GCOS.

A specific subset of the GCOS observing activities for 2008 and 2009 (and into 2010) are the USGCRP-sponsored polar climate observations made in cooperation with the International Polar Year (IPY). During 2009, IPY will come to a formal conclusion; however, many polar observing systems will continue to operate. Several agencies are working together to establish an Arctic Observing Network that will build on systems deployed during IPY and provide for coordinated efforts to sustain key climate observations. This cooperation will extend to international partners to encourage a pan-Arctic approach to observation and data sharing.

Remotely sensed observations continue to be a cornerstone of the USGCRP. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) lidar and CloudSat radar instruments are providing an unprecedented examination of the vertical structure of aerosols and clouds over the entire Earth. These data—when combined with data from the Aqua, Aura, and PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar) satellites orbiting in formation (the "A-Train")—will enable systematic pursuit of key issues including the effects of aerosols on clouds and precipitation, the strength of cloud feedbacks, and the characteristics of difficult-to-observe polar clouds. The increasing volume of data from remote-sensing and *in situ* observing systems presents a continuing challenge for USGCRP agencies to ensure that data management systems are able to handle the expected increases.

HIGHLIGHTS OF RECENT RESEARCH – OBSERVATIONS AND MONITORING

The following are selected highlights of observation and monitoring activities supported by USGCRP-participating agencies. The principal focus of this section is on describing progress in implementing the observations that contribute to the USGCRP mission. As a result, the section touches on some observing systems that are crucial to the USGCRP but are not included within the USGCRP budget because they primarily serve other purposes. A more thorough review of the state of observing systems can be found in the recently published report, *The United States National Report on Systematic Observations for Climate for 2008: National Activities with Respect to the Global Climate Observing System (GCOS) Implementation Plan*.[1] This report was prepared for the United Nations Framework Convention on Climate Change in September 2008 with the express purpose of reporting on progress on the implementation of the global observing system for climate.

Surface Climate Observations. All 114 of the planned U.S. Climate Reference Network (USCRN) stations in the conterminous United States have been formally commissioned for operations. In 2008, planning began to field an additional 29 USCRN sites in the State of Alaska, and the U.S. GCOS program has funded some initial prototype sites in both Alaska and Hawaii. A USCRN system is planned for deployment

at the Russian Arctic site of Tiksi (71.5°N) in summer 2009 in order to provide long-term reference measurements of temperature, precipitation, wind, pressure, and surface radiation in support of IPY and beyond.

Arctic Sea Ice Retreats and Thins—A New State?[2,3,4] The summer extent of the Arctic sea ice cover, widely recognized as an indicator of climate change, has been declining for the past few decades and reached a record minimum in September 2007. The past persistent positive state of the Arctic Oscillation forced much thick ice to leave the Arctic via the Fram Strait. General warming, normal summer insolation and the ice-albedo feedback, and unusual southerly winds in the Pacific sector of the Arctic during summer 2007 resulted in unusual melt of sea ice at that time. Recent observations of ice thickness have shown thick ice to be mostly limited to areas just north of the Canadian Arctic Archipelago, leading to speculation that the situation observed in summer 2007 represents a "new state" for Arctic sea ice. Continued research and observations will be needed to validate the "new state" and understand its consequences for the Arctic and the globe.

Initial Ocean Observing System for Climate Reaches 60% Completion. USGCRP agencies joined with 72 other nations in implementing the internationally vetted design of an initial ocean observing system for climate, articulated in the plan for GCOS developed under the auspices of WMO, the IOC, and the United Nations Environment Programme. Deployment of the observing system, planned for completion in 2013, is proceeding, with the United States currently supporting nearly 50% (3860 of 7723) of the ocean-based observing platforms.

Sustained Ocean Observations Demonstrate Increasing Evaporation.[5] A newly developed methodology, combining multiple satellite retrievals, ship-based observations, and surface meteorology from numerical weather prediction reanalyses, evaluated using over 100 air-sea observational time series from *in situ* ocean platforms, has demonstrated that evaporation of water from the world's oceans has increased by about 10% since the late 1970s. The new evaporation data set uniquely blends the broad spatial coverage of satellites and models with the high accuracy of *in situ* observations to better evaluate the impact of rising ocean temperatures on the Earth's hydrological cycle. The oceans account for 86% of global evaporation, whose rate of increase is consistent with that of independently measured atmospheric moisture. The potential consequences of an evolving water cycle include impacts on droughts, floods, and water resources.

Global Coverage Achieved by the Argo Profiling Array. In 1998, an international consortium presented plans for an array of 3,000 autonomous instruments that would revolutionize the collection of climate-relevant information from the upper 2 km of the world's oceans—the Argo array. These instruments drift at depth, periodically rising to the sea surface, collecting data along the way, and report their observations in real time via satellite communications. The initial deployment objective of 3,000 instruments distributed homogenously throughout the world's oceans has been attained, and the array now provides over 100,000 high-quality temperature and salinity profiles annually along with global-scale velocity data, all without a seasonal bias. The Argo array was deployed through the collaboration of more than 40 countries and the European Union. Argo is a remarkable achievement that is revolutionizing our ability to understand and describe the oceans' role in climate. While having achieved this initial goal, the challenge to maintain the array, particularly in the Southern Hemisphere, has increased. Access to deployment platforms (ships and aircraft) has dramatically decreased over the last two years, with the program only being able to address large voids in the array as they appear instead of maintaining a routine, systematic schedule to reseed the array before major gaps appear.

Autonomous Observations of the Biological Carbon Pump in the Global Ocean.[6] Marine phytoplankton in the world's oceans account for roughly half of

global primary productivity. Particulate organic and inorganic carbon (POC and PIC), consisting of aggregates containing the remains of phytoplankton and other living and non-living material, sinks below 100 m to the deep ocean globally at a rate of approximately 10 GtC per year. This very fast process, also known as the "biological carbon pump," is a principal determinant of the vertical distribution of carbon in the ocean and hence is a major factor governing the exchange of carbon dioxide (CO_2) with the atmosphere. All aspects of the concentration and sedimentation of POC and PIC in the oceans are poorly understood due to the need for frequent (daily) *in situ* measurements at a wide variety of locations and for extended periods of time—something that ships and humans cannot do well. Extensive measurements are central to understanding the ocean carbon cycle and projecting how it will be modified by climate change. To date, 12 low-cost ocean profiling floats (called Carbon Explorers) have been deployed to follow the day-to-day variations of carbon biomass profiles to kilometer depths in biologically dynamic and extreme environments, such as the "howling 50s" of the Southern Ocean. The combination of in-water physical parameters and optics from Explorers and satellite remotely sensed properties (including ocean color) provides a powerful framework for understanding bio-carbon ocean dynamics. The newest robotic Carbon Flux Explorer (see Figure 16) can observe carbon sedimentation on hourly time scales continuously for seasons to years.

Surface-Based Observatories of Clouds and Radiation.[7,8,9,10,11,12,13] The Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) is a scientific user facility for obtaining continuous, long-term measurements of radiative fluxes, cloud and aerosol properties, and related atmospheric characteristics in diverse climate regimes. The ACRF paradigm of long-term continuous measurements is essential to the evaluation and enhancement of climate models that must simulate the evolution of atmospheric properties for long continuous periods (from decades to centuries). The ACRF expands its geographic coverage through deployments of a mobile facility and includes aerial measurements that complement the ground measurements. In 2008, the mobile facility was deployed to China to examine aerosol indirect effects. In 2009, the mobile facility will begin a two-year deployment to the Azores to study processes controlling the radiative properties and microphysics of marine boundary layer clouds, a high-priority science question. An IPY experiment was conducted using combinations of

Autonomous Measurement of Ocean Carbon Flux Profiles

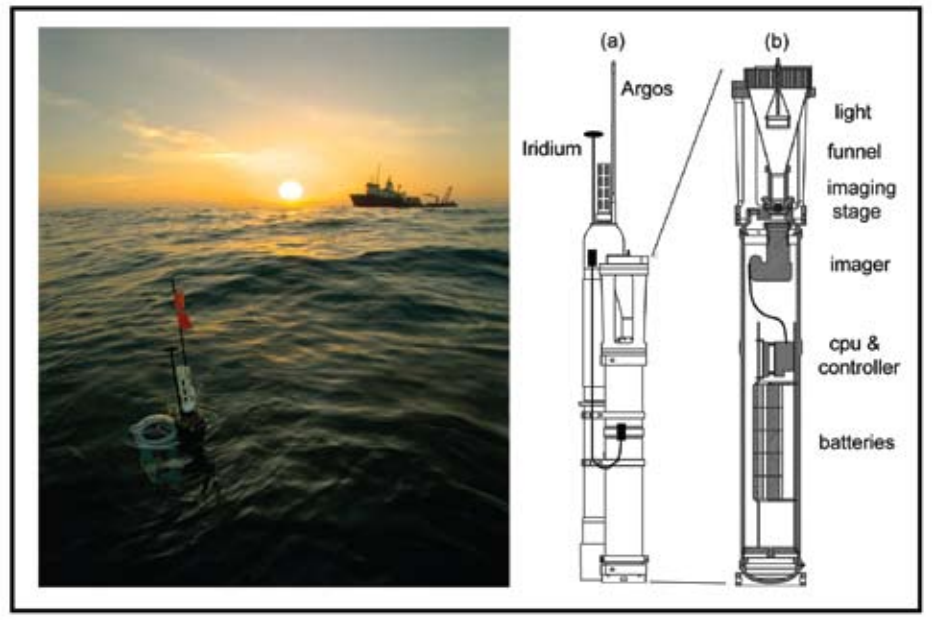

Figure 16: Left: the Carbon Flux Explorer at dawn near San Diego awaiting recovery after its first two day mission monitoring carbon sedimentation at depths of 800 m. Schematics on right illustrate (a) the Carbon Flux Explorer, the integration of Berkeley Lab's Optical Sedimentation Recorder (OSR) and Scripps' Sounding Oceanographic Lagrangian Observer (SOLO) profiling float. (b) Detail of the OSR. The SOLO communicates to the OSR its dive status and pending actions. The OSR communicates reduced data to the SOLO for real-time relay to Iridium satellites and shore. *Credit: J.K.B. Bishop, University of California.*

ground and aerial measurements. Data from the IPY experiment will be used as a case study by the Global Energy and Water Cycle Experiment (GEWEX) Cloud Systems Study.

Climate Absolute Radiance and Refractivity Observatory (CLARREO).[14] The CLARREO mission was recommended by the National Research Council (NRC) Decadal Survey as a key component of the future climate observing system. NASA and NOAA share responsibility for CLARREO. The NOAA component involves the continuity of measurements of incident solar irradiance and Earth's energy budget by flying the Total Solar Irradiance Sensor (TSIS) and Clouds and the Earth's Radiant Energy System (CERES) sensors that were removed from the National Polar-Orbiting Operational Environmental Satellite System (NPOESS). In support of this mission, the final version of the CERES radiation budget instrument has been added for flight on the NPOESS Preparatory Project (NPP) mission, scheduled to launch in 2010. This addition is to avoid a gap in the long-term climate record critical to observing decadal changes in cloud feedback. Climate modeling studies have shown that decadal changes in net cloud radiative effect are linearly related to the strength of cloud feedbacks. A CERES Flight Model 6 instrument is planned for flight in concert with the NPOESS C1 platform. Observations of natural climate variability suggest that signals from cloud feedback should rise above climate system noise by about 2015 to 2020 if the radiation budget record can avoid gaps before then. NOAA and NASA are collaborating on this first portion of CLARREO. The second portion of CLARREO involves the measurement of spectrally resolved thermal infrared radiation and reflected solar radiation at high absolute accuracy. Coupled with measurements from onboard global positioning system (GPS) radio occultation receivers, these measurements will provide a long-term benchmarking data record for the detection, projection, and attribution of changes in the climate system across a wide range of climate variables. In addition, the radiances traceable to the International System of Units will provide a source of absolute calibration for a wide range of visible and infrared Earth observing sensors, greatly increasing their value for climate monitoring. In this way, CLARREO will leverage a wide range of satellite-based observing elements of GCOS. This second benchmarking and inter-calibration part of CLARREO is currently active in pre-phase A mission definition studies.

NASA A-Train. The "A-Train" is a sun-synchronous Earth-orbiting satellite formation that studies the atmosphere (the A in A-Train stands for afternoon), and is a collaboration between NASA and the space agencies of Canada and France. The A-Train constellation consists of five satellites flying in close proximity to each other. The first satellite in the A-Train constellation, Aqua, was launched in 2002. The second satellite, Aura, was launched in June 2004, the CloudSat and CALIPSO satellites in April 2006, and the PARASOL satellite in December 2004. The A-Train satellites cross the equator within a few minutes of one another at around 1:30 p.m. local solar time. By combining the different sets of observations from the A-Train, a better understanding of atmospheric composition, clouds, and aerosols has resulted that has led and is leading to major advances in atmospheric knowledge. More details on the five A-Train components are as follows:

- The NASA Aqua satellite carries six instruments focused on the multi-disciplinary study of Earth's interrelated processes (atmosphere, oceans, and land surface) and their relationship to changes in the Earth system. The six instruments are the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU-A), the Humidity Sounder for Brazil (HSB), the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), the Moderate Resolution Imaging Spectroradiometer (MODIS), and Clouds and the Earth's Radiant Energy System (CERES).
- The NASA Aura satellite was launched in July 2004 with four instruments to extensively monitor the composition of the atmosphere. Two of these instruments, the Microwave Limb Sounder (MLS) and High Resolution Dynamics Limb Sounder (HIRDLS), make limb-viewing observations to obtain highly resolved altitude profiles of the stratosphere and upper troposphere for understanding photochemical and dynamical processes in these altitude ranges. The Tropospheric Emission Spectrometer (TES) measures column and partial altitude profiles of ozone and tropospheric trace gases, while the Ozone Monitoring Instrument (OMI) obtains nearly daily global ozone column maps as well as column measurements of other important air quality parameters. Aura observes the atmosphere to

answer the following three high-priority environmental questions: (1) is the Earth's ozone layer recovering; (2) is air quality getting worse; and (3) how is the Earth's climate changing?

- PARASOL is a French CNES microsatellite project. It has improved the characterization of cloud and aerosol microphysical and radiative properties. This has led to a substantial increase in our understanding of the radiative impact of clouds and aerosols that in turn has led to improving numerical modeling of these processes in general circulation models.
- CALIPSO's payload consists of three co-aligned nadir-viewing instruments that include a cloud-aerosol sensing lidar, an imaging infrared radiometer, and a visible wide field camera.
- The CloudSat research satellite payload consists of a nadir-looking cloud profiling radar which measures the power backscattered by clouds as a function of distance from the radar.

High Resolution Dynamics Limb Sounder (HIRDLS). USGCRP scientists have made significant progress in improving the retrieval algorithms for the HIRDLS instrument on the Aura research satellite. This instrument suffered from a blockage of most of its field of view during the launch of the satellite in 2004, which required a significant amount of time to characterize the radiances from the blockages on each of its observation channels. The HIRDLS team produced validated ozone and temperature profiles at much higher vertical resolution than previously achieved from space. HIRDLS high-resolution temperature measurements show short vertical wavelength gravity waves and their forcing on stratospheric circulation that will be used in general circulation models in 2010. HIRDLS now also has scientifically useful profile retrievals of the chlorofluorocarbons CFC-11 and CFC-12 to be used in the upcoming WMO Ozone Assessments. New measurements of cloud top heights and aerosol extinction will be used to refine climate models. In early 2010, HIRDLS will be measuring methane and nitrous oxide, and these data sets will provide researchers new data with high vertical resolution in the upper troposphere/lower stratosphere and higher that will improve our understanding of the various atmospheric chemical transport processes.

Aerosol Robotic NETwork (AERONET) and MicroPulse Lidar NETwork (MPLNET).[15] AERONET is a system of globally distributed autonomous sun-photometers established in the early 1990s to support atmospheric studies at various scales through standardized measurements of the direct sunlight and diffuse skylight. It has provided precise measurements of aerosol optical properties, facilitating the creation of an accurate global aerosol climatology, and aiding the validation of satellite remote-sensing products. MPLNET measures the vertical profiles of aerosols and clouds at geographic sites collocated with AERONET. Both of these systems continue to provide

Surface Calibration of Satellite Ocean Color Observations

Figure 17: The AERONET sun-photometer used to measure water-leaving radiances and downwelling solar radiances atop the Gustav Dalen Lighthouse platform in the BalticSea, about nine km off of the Swedish coast. The panel to the right shows a close-up view of the sun-photometer on the platform. *Credit: B. Holben, NASA/Goddard Space Flight Center.*

data useful for scientific investigations of aerosols and clouds as well as for calibration and validation of satellite instruments currently in operation (e.g., MODIS, Multi-angle Imaging Spectroradiometer (MISR), CALIPSO, Glory). Recent development of an ocean color component of AERONET provides support for long-term satellite ocean color investigations through consistent and accurate measurements collected by autonomous radiometer systems deployed on offshore fixed platforms. The new data product, normalized water-leaving radiances, is measured at the same wavelengths in the visible and near-infrared spectral regions as the aerosol products.

HIGHLIGHTS OF RECENT RESEARCH – DATA MANAGEMENT AND INFORMATION

The following are selected data management and information activities supported by USGCRP-participating agencies.

Carbon Dioxide Information Analysis Center (CDIAC). The CDIAC provides comprehensive, long-term data management support, analysis, and information services to the USGCRP, the global climate research community, and the general public. The CDIAC data collection is designed to answer questions pertinent to both the present-day carbon budget and temporal changes in carbon sources and sinks. These data sets provide quantitative estimates of anthropogenic CO_2 emission rates, atmospheric concentration levels, land-atmosphere fluxes, ocean-atmosphere fluxes, and oceanic concentrations and inventories. In 2008, CDIAC augmented its ocean holdings by offering CO_2 measurements from buoys, research cruises, and volunteer observing ship lines along U.S. coastlines to support the North American Carbon Program (NACP). In 2008, CDIAC also released the final Carbon Dioxide in the Atlantic Ocean (CARINA) synthesis database including both discrete and underway measurements.

Annual State of the Climate Report—Using Earth Observations to Monitor the Global Climate.[16] In partnership with WMO, along with numerous national and international partners, a State of the Climate monitoring effort has been established, which consists of operational monitoring, analysis, and reporting on atmosphere, ocean, and land surface conditions from the global to local scale. By combining historical data with current observations, this program places present-day climate in historical context and provides perspectives on the extent to which the climate continues to vary and change as well as the effect that climate is having on societies and the environment. More than 150 scientists from over 30 countries are now part of an annual process of turning raw observations collected from the global array of observing systems into information that enhances the ability of decisionmakers to understand the state of the Earth's climate and its variation and change during the past year, with context provided by decades to centuries of climate information. Many observing and analysis systems are unique to countries or regions of the world, but through this effort, the information from each system is openly shared and has proven essential to moving data into operational use and filling critical gaps in current knowledge about the state of the global climate system. It seeks to report on as many of the Essential Climate Variables (ECV) as possible as identified by the GCOS Second Adequacy Report. The 2007 edition of this report was published in July 2008, in its eight years of publication the number of monitored ECVs has doubled to a total of 22.

Advances in Quality and Accessibility of Satellite-Based Sea Surface Temperatures.[17] Since 2002, several related activities have been converging to significantly improve the quality of and access to satellite-based sea surface temperature (SST) observations and analyses. The newly named Group for High Resolution SST (GHRSST) consolidated these activities in 2008. The GHRSST framework makes available consistently formatted SST observations from available operational and research satellite instruments. All of these observations include bias and standard deviation uncertainty estimates as well, representing a significant advance in the usefulness of the SST data for a wide variety of applications. The dramatically enhanced availability of the data through a Global Data Assembly Center at the NASA Physical Oceanography Distributed Active Archive Center[18] and through the Long Term Stewardship and Reanalysis Facility at NOAA's National Oceanographic Data Center[19] has resulted in many new blended, multi-sensor SST analysis products. These products include optimally interpolated SST reanalysis products available on a daily, 25-km resolution going back to 1985 and several

daily global analysis products available at better than 10-km resolution. The near-real-time versions of these products are submitted to an SST intercomparison framework[20] and a High Resolution Diagnostic Data Set system[21] as well. The retrospective products are being connected to historical reconstructions of *in situ* SST via a GCOS SST Intercomparison facility hosted at the National Oceanographic Data Center Long-Term Stewardship and Reanalysis Facility,[22] where the major reconstructions have been converted to GHRSST standard format and subjected to a common set of diagnostics. In addition, SST measurements such as those from the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder[23] and the European Advanced Along-Track Scanning Radiometer (AATSR) series of instruments are actively being reprocessed and reformatted to GHRSST standards and will be made available through the same set of data access and intercomparison facilities.

HIGHLIGHTS OF PLANS FOR FY 2010

The USGCRP will continue to develop and implement integrated systems for observing and monitoring global change, and the associated data management and information systems. Selected key planned activities for FY 2010 and beyond follow.

GCOS Reference Upper Air Network (GRUAN).[24,25] Work continues on developing this key reference climate system. GRUAN is intended to aid in enhancing the quality of upper tropospheric and lower stratospheric water vapor measurements at a subset of 30 to 40 global stations. GRUAN began operation on 1 January 2009, and is led by the GRUAN Lead Center in Lindenberg, Germany. Seven U.S. stations (including five DOE ARM sites and one NOAA/NCAR site) were invited to be part of the initial configuration of stations. GRUAN is a key contributing network to GCOS, and GCOS in turn is the formal climate component of the Global Earth Observing System of Systems (GEOSS) as outlined in the ten-year GEOSS Implementation Plan. GRUAN contributes to the GEOSS goal of "understanding, assessing, predicting, mitigating, and adapting to climate variability and change." GRUAN is also a key element supporting the Global Space-Based Inter-Calibration System (GSICS) effort.

Clouds with Low Optical Water Depths Optical Radiative Observations. The breadth of climate sensitivity estimates among general circulation models arises primarily from inter-model differences in the representations of aerosol and cloud processes; in particular, low-level boundary-layer clouds constitute the largest uncertainty in climate models. This is due to large discrepancies in the radiative responses simulated by models in regions dominated by low-level cloud cover, and to the large areas of the globe covered by these regions. Further, the properties of thin, low-level clouds are very sensitive to changes in aerosol loading, and the aerosol effect on cloud albedo remains the dominant uncertainty in radiative forcing. These issues will be addressed in 2009 by a field campaign to be conducted at the ARM Southern Great Plains site, with long-term, systematic flights in which the environmental conditions and physical characteristics of low-altitude, liquid-water clouds will be sampled. Different from the typical short-duration aircraft campaigns, this field experiment will run for nine months to obtain for the first time representative *in situ* statistics of cloud properties and their seasonal variations, which are needed for model improvements.

These activities will address Goals 12.2 and 12.5 of the 2003 Strategic Plan.

Liquid and Mixed Phase Clouds Experiment—ARM Mobile Facility. In 2010, an ARM Mobile Facility will continue its deployment in the Azores to study processes controlling the radiative properties and microphysics of marine boundary layer clouds, a high-priority science question. In late 2010, a second ARM mobile facility will be deployed to the Storm Peak Lab (SPL) cloud and aerosol research facility located east of Steamboat Springs, Colorado. SPL is located at an altitude of 3,210 m above sea level and is above the cloud base 25% of the time during the winter season. The objective of the experiment is to address the critical shortage of correlative data that can be use for validation and development of new algorithms. This data set will enhance the ability to convert the remote-sensing measurements to cloud properties. Such correlative data sets are normally created by episodic and expensive aircraft measurements. This experiment has the potential to create a correlative data set equivalent to between 200 and 300 aircraft flights in liquid and mixed phase clouds. This experiment will enhance the development of data sets used for model development and evaluation.

Small Particles in Cirrus (SPartICus). A primary USGCRP goal is to characterize the properties of clouds so that their representation can be improved in general circulation models, and the program has compiled remote-sensing data from ground sites since the early 1990s. Cirrus clouds are a critical link in this problem because they exert significant controls on the Earth's radiation budget. Using state-of-the-science instrumentation, the Small Particles in Cirrus (SPartICus) project will address the present state of uncertainty of the retrievals and advance our understanding of mid-latitude cirrus by collecting *in situ* data over a period of 6 to 10 months. The resulting data set will be used to investigate 1) the degree to which small particles (i.e., <50 μm diameter) contribute to the mass and radiative properties of mid-latitude cirrus and 2) the role of cloud-scale dynamical processes in the evolution of cirrus properties through nucleation, particle growth, and sublimation. The experiment will span the occurrence of jet stream cirrus over the Southern Great Plains ARM site that begins in autumn and extend to the period when convective cirrus clouds are frequent during spring. An intensive phase of the project could focus more on microphysical processes and field a more extensive set of experimental probes that observe the aerosol and ice nuclei properties of the upper troposphere.

Arctic Lower Troposphere Structure (ALTOS). The ACRF will conduct *in situ* cloud and aerosol measurements of the Arctic lower troposphere (lower 2 km) for a two-month period during the fall transition season of 2010. This experiment will use a tethered balloon system equipped with state-of-the art atmospheric state, cloud microphysics, radiation, and aerosol sampling devices for routine sampling of the cloudy lower troposphere at Oliktok Point on the North Slope of Alaska. Recent studies suggest that the observed Arctic sea ice retreats, as depicted by the summer ice edge, are correlated closely with an upward trend in the downwelling, long-wave radiative flux in the Arctic spring. The increase in the radiative flux appears to be driven mostly by increases in clouds and precipitable water vapor, thus these data can be used to better understand the contribution of clouds in this important feedback process. This unique data set of *in situ* cloud microphysics, aerosol, and radiative measurements will provide a thorough test for parameterizations of Arctic cloud processes, and secondly, a test for the set of cloud property retrieval

algorithms developed by the ARM and other national programs.

NPP and NPOESS Climate Monitoring. The climate monitoring capabilities of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) (launch expected in 2010) and afternoon overpass NPOESS platforms (launches expected in 2013 and 2020) were augmented substantially in 2008. Following a major program downsizing exercise in 2006, the NPP and afternoon NPOESS platforms were slated to each carry a multispectral imager, a thermal infrared and microwave sounder suite, a wide-field ozone nadir sensor, and an Earth radiation budget sensor (CERES; on the NPOESS 2013 launch only). Other planned climate sensors, however, were demanifested at that time. Following an extensive study period, the President announced plans in early 2008 to add CERES and an ozone limb profiler to the NPP platform, and to complement CERES with a comprehensive solar irradiance monitor (TSIS) on the NPOESS 2013 platform. These "remanifestations" significantly reduce the risk of near-term gaps in several key long-term climate observations. The FY 2009 budget also included funding to develop initial Climate Data Records from NPP/NPOESS and their legacy missions.

These activities will address Goals 12.3 and 12.5 of the 2003 Strategic Plan.

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10 COMMUNICATIONS

In its *2003 Strategic Plan*, the program identified communications as one of four core approaches for achieving its five overarching scientific goals. The USGCRP is committed to communicating with interested partners in the United States and throughout the world, and to learning from these partners on a continuing basis. As an essential part of its mission, the USGCRP stresses openness and transparency in its findings and reports.

The Communications Interagency Working Group (CIWG), established during FY 2004, develops and executes an implementation plan each year that focuses on disseminating the results of USGCRP activities credibly and effectively and making USGCRP science findings and products easily available to a diverse set of audiences. Elements of the implementation plan for calendar year 2009 included:

- *Media Relations*–When requested by the USGCRP Director, assist in communicating on matters relating to climate science, with particular focus on the delivery of the remaining Synthesis and Assessment Products (SAPs).
- *Public Outreach*–Develop materials and methods for public outreach on issues related to climate science and the activities and products of the USGCRP.

- *Legislative outreach*–Develop materials for congressional briefings in association with lead agencies.
- *Web Sites*–Develop and advance a strategy for improving, integrating, and promoting the content of web sites operated or supported by the USGCRP and its participating agencies, recognizing that the sites are essential communication and outreach tools.

The elements and strategies described above were particularly focused around the release of the SAPs listed in Chapter 8 of this report. When the final products were released, the teams associated with each SAP could request the CIWG's assistance in generating outreach products or activities via the lead agency and the lead agency's representative to the CIWG. These products and activities included:

- Constituent briefings
- Web links posted on participating agency and USGCRP home pages
- Press releases
- Public comments package posted on web sites
- Fact sheets and other summary material, such as talking points for authors
- Scientific posters.

Agencies represented on the CIWG also incorporate the results of SAPs into their outreach materials. For example, USGS has podcast interviews on its web site, including the results of SAP 1.2, 4.2, and 3.4, and EPA has included reference to SAP 4.1 in its web-based general public information on sea level rise.

The U.S. Global Change Research Program Office (USGCRPO), funded and supervised by the agencies and departments participating in the USGCRP, supports the program's communications goals, along with members of the CIWG. USGCRPO assists CIWG, coordinates preparation of the annual *Our Changing Planet* report to Congress as well as other reports, and is responsible for managing the program's interagency web sites, printing and editing crosscutting fact sheets, and facilitating opportunities for interagency participation in outreach for SAPs and other Federal science.

HIGHLIGHTS OF RECENT INTERAGENCY COMMUNICATIONS ACTIVITY

Listed below are highlights of recent communication activities coordinated at the interagency level (as of 30 June 2009):

- Published and distributed (in both hardcopy and online) the FY 2009 edition of *Our Changing Planet*, the program's annual report to Congress and the President.
- Completed production and distribution of the remaining 13 SAP final reports, including a series of briefings and other activities focused on communicating the report findings. Chapter 8 of this report provides a complete list of the 21 SAPs, including descriptions of their contents and completion dates. SAP outreach activities in the current reporting period were as follows:
  - SAP 1.2: *Past Climate Variability and Change in theArctic and at High Latitudes* (January 2009)
  - SAP 1.3: *Re-analyses of historical climate data for key atmospheric features. Implications for attribution of causes of observed change.* (November 2008)
  - SAP 2.3: *Aerosol properties and their impacts on climate* (January 2009)
  - SAP 2.4: *Trends in emissions of ozone-depleting substances, ozone layer recovery, and implications for ultraviolet radiation exposure* (November 2008)
  - SAP 3.1: *Climate Change Models: An Assessment of Strengths and Limitations* (July 2008)
  - SAP 3.2: *Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols* (September 2008)
  - SAP 3.4: *Abrupt Climate Change* (December 2008)
  - SAP 4.1: *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* (January 2009)
  - SAP 4.2: *Thresholds of Change in Ecosystems* (January 2009)
  - SAP 4.4: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources* (June 2008)
  - SAP 4.6: *Analyses of the effects of global change on human health and welfare and human systems* (July 2008)
  - SAP 5.1: *Uses and limitations of observations, data, forecasts, and other projections in decision support for selected sectors and regions* (September 2008).
  - SAP 5.2: *Best practice approaches for characterizing, communicating, and incorporating scientific uncertainty in decisionmaking* (January 2009)
  - SAP 5.3: *Decision support experiments and evalua tions using seasonal to interannual forecasts and observational data* (November 2008)
- Posted online drafts of SAP reports for public comment. All submitted public comments also were posted, along with the authors' responses.
- Posted peer review comments on draft SAP reports, along with the authors' responses.
- Advisory committees for many of the SAPs convened public meetings to discuss report drafts. All meetings were announced in the Federal Register.
- Managed and improved USGCRP web sites, including web services to facilitate interagency collaboration. Conducted surveys of web use and redesigned web sites in accordance with these results and with CIWG expertise (using a contracted design firm for the graphic redesign).
- Managed the Global Change Research Information Office (GCRIO) as mandated by the Global Change Research Act of 1990, including a catalog for requesting reports.
- Answered questions from the public regarding products and services as well as educational and scientific enquiries
- Managed the Climate Change Technology Program (CCTP) public web site and provided additional services such as development and management of password- protected web sites and publications support

HIGHLIGHTS OF PLANS FOR FY 2010

Listed below are some of the communications activities coordinated at the interagency level and planned for late FY 2009 (July to September 2009) and early FY 2010 (October 2009 to May 2010):

- Continuing to facilitate workshops and listening sessions to engage the broader community in accessing and using climate data and information.
- Produce and distribute the *Global Climate Change Impacts in the United States* report that consolidates the information contained in the 21 SAPs, the recent IPCC reports, and other recent results that have appeared in the scientific literature. This report provides a single coherent analysis of the current understanding of climate change science, summarizing the contributions of the USGCRP Program, and identifying important gaps in the science. The CIWG will advise the lead agencies

on communications- related issues including dissemination to appropriate stakeholders, briefings, press releases, and summaries for a range of audiences across different information media.

- Prepare and disseminate the FY 2010 edition of *Our Changing Planet*.
- Continue to improve and expand web sites by preparing and posting new content, improving web site usability and accessibility, and enhancing agency integration. This will involve initiating greater focus throughout the agencies to facilitate true interoperability of climate and global change information across government web sites—blending information in a dynamic way from agency sites accessible via a USGCRP gateway site housed at the USGCRP.

11 INTERNATIONAL RESEARCH AND COOPERATION

Cooperation and coordination at an international scale, including research, observations, data, and information sharing are critical to advancing understanding of changes in the climate and related systems and informing our decisions about adaptation, mitigation, and development measures domestically and internationally. The USGCRP, the individual agencies that compose the USGCRP, its various interagency working groups, and, in particular, the Interagency Working Group on International Research and Cooperation interact with a wide range of international research activities that collectively cover the broad spectrum of global environmental change research.

Through its active participation and leadership, the USGCRP and the large community of U.S. scientists supported by or associated with it truly has a global reach. Activities in which the United States is involved include supporting global environmental change research programs including, but not limited to, those that operate under the aegis of the International Council for Science (ICSU); supporting international assessments, particularly the Intergovernmental Panel on Climate Change (IPCC); supporting regional global change research networks; playing an active role in informal international organizations that are involved with the advancement of global environmental change research; and participating in and in many cases leading international efforts to advance coordination and cooperation around observation of the Earth.

Individual USGCRP agencies support international activities that are aligned with their goals or missions. In some cases, an agency will be given the lead for a particular effort for the Federal Government; this may involve intra- and/or interagency coordination as well as funding, including in-kind support, depending upon the organization. The USGCRP also provides a very useful channel for communication and

coordination, both within the Federal Government and with the broader scientific community, for exchange of global change-related information and for providing input to various international organizations. This support includes work with the Department of State at a variety of levels, but particularly with respect to the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC) as well as bilateral arrangements in climate change science and technology. This also includes contributions to and participation in international observational efforts such as the Group on Earth Observations (GEO) and the Global Climate Observing System (GCOS).

The USGCRP provides the core of the U.S. portion of funding for international coordination of global change research. This includes support for the U.S.-hosted IPCC Working Group II Technical Support Unit. USGCRP support is also provided to the partner programs of the Earth System Science Partnership (ESSP) including the SysTem for Analysis, Research, and Training (START). The NSF acts on behalf of the USGCRP to manage U.S. support for regional global change research networks, including the Inter-American Institute for Global Change Research (IAI), the Asia-Pacific Network (APN), and the emerging African Network for Earth System Science (AfricanNESS).

The international global change research programs continue to provide sound frameworks for core research projects, capacity building programs, and regional networks. These programs include the World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP), DIVERSITAS (an international biodiversity science program), ESSP, and START. The key regional programs are APN, IAI, AfricanNESS, and several regional programs under the START umbrella (Southeast Asia Regional Centre, Temperate East Asia Regional Committee, etc.). These regional programs, due to their ability to bring together national networks of global change scientists in an international setting, are increasingly being called upon to provide input to international organizations, international assessments, and other activities.

The USGCRP Interagency Working Group on International Research and Cooperation facilitates the centralized operations of and U.S. participation in the international global change research programs by serving as a channel through which "glue money" is provided to these programs. The glue money provided by the USGCRP and individual agencies facilitates leadership by U.S. scientists in these organizations and advances overall U.S. global change research, modeling, and observations. The U.S. funding leverages substantial funding of these programs by other countries (that in most cases is of the order of two or three times the funding provided by the United States).

The following sections describe highlights of recent activities as well as future plans of these international global change research programs and of related interagency international efforts. For more detailed information about some of these activities, see Chapter 15 of the *2003 Strategic Plan*.

HIGHLIGHTS OF RECENT ACTIVITIES

Needs of Developing Countries to Adapt to Climate Change.[1] In August 2008, the Department of State, leading an interagency group, released a *Report to Congress on the Needs of Developing Countries in Adapting to Climate Change Impacts*. The interagency group worked to evaluate the needs of developing countries and describe planned and needed actions to address those needs. These activities include scientific research to understand processes that underlie climate change, analyzing data from Earth observations, developing decision support tools, and integrating climate information into development programs and projects.

Intergovernmental Panel on Climate Change. Following the highly successful completion of the Fourth Assessment Report, elections of the new IPCC Bureau were held in September 2008. Leadership for Working Group I was awarded to Switzerland and China, with Dr. Thomas Stocker of the University of Bern and Dahe Qin of the China Meteorological Administration serving as co-chairs. Leadership of Working Group II was awarded to Dr. Chris Field of the United States and Vicente Barros of Argentina. Drs. Field and Barros will oversee development of the Impacts, Adaptation, and Vulnerability (IAV) volume of the Fifth Assessment Report, and any

Special Reports and/or Technical Papers agreed upon by the Panel in response to specific IAV queries of the UNFCCC, its subsidiary bodies, and/or other United Nations entities. A scoping meeting will be held in July 2009 in Venice in which chapter outlines for the three Working Group contributions and a broad outline for the Synthesis Report will be developed.

Bilateral Cooperation in Climate Change Science and Technology.[2, 3] Since June 2001, the United States has launched bilateral climate partnerships with 15 countries and regional organizations that, combined with the United States, account for almost 80% of global greenhouse gas emissions. Partnerships have been established with Australia, Brazil, Canada, China, Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama), the European Union, Germany, India, Italy, Japan, Mexico, New Zealand, the Republic of Korea, the Russian Federation, and South Africa. These bilateral initiatives seek to build on key elements of the USGCRP and the Climate Change Technology Program, including research, observations, data management and distribution, and capacity building. These partnerships now encompass well over 400 (474) individual activities. Successful joint projects have been initiated in areas such as climate change science; clean and advanced energy technologies; carbon capture, storage, and sequestration; and policy approaches to reducing greenhouse gas emissions. The United States is also assisting key developing countries in efforts to build the scientific and technological capacity needed to address climate change. Two ongoing objectives for the bilateral activities will be continued advancement of results-oriented programs and the fostering of substantive policy dialogs within all of the bilateral climate change partnerships. In order to broaden U.S. cooperative efforts to advance a practical and effective global response to climate change, the United States will expand outreach and support to the developing country community, utilizing a regional approach where feasible.

DIVERSITAS.[4, 5] DIVERSITAS is an international research program that provides integrative biodiversity science including research on global environmental change and its impacts on biodiversity. In calendar years 2007 and 2008, DIVERSITAS, with NASA, continued to lead the establishment of a global biodiversity observing

system, called Group of Earth Observations-Biodiversity Network (GEO-BON). DIVERSITAS continued in its work to advance biodiversity science through its core projects and targeted activities including workshops, field experiments, and other activities. These activities covered a broad spectrum of the field including biodiversity and health, ecosystem services, climate change, and other issues. Efforts continued to develop an international biodiversity assessment and contributed to the United Nations Convention on Biological Diversity (CBD).

Earth System Science Partnership.[6,7] The ESSP, a partnership of the four international global environmental change research programs (DIVERSITAS, IGBP, IHDP, and WCRP) continues to provide leadership to catalyze very important new integrative, interdisciplinary studies of the Earth system. The Global Carbon Project's Carbon Budget 2007 report was a significant contribution to international discussions of carbon dioxide (CO_2) emissions mitigation. The Global Environmental Change and Food Systems project (GECAFS) hosted

an international conference on Food Security and Climate Change in April 2008 at Oxford University, United Kingdom. GECAFS also published and widely distributed regional science plans for Southern Africa, the Caribbean, and the Indo-Gangetic Plain. ESSP also has established a promising new partnership with the Consultative Group on International Agriculture Research (CGIAR) designed to address gaps in critical information necessary to manage the tradeoffs between food security, livelihood, and environmental goals in the face of global environmental change. The ESSP also continued implementation of the Global Water System Project, the Global Environmental Change and Human Health project, and the Monsoon Asia Regional Study. The ESSP also continued to contribute to the UNFCCC Subsidiary Bodies for Science and Technological Advice (SBSTA).

International Council for Science.[8] ICSU, with the International Group of Funding Agencies for Global Change Research (IGFA), has led and completed the reviews of the ESSP, the IGBP, and the WCRP. A review of the DIVERSITAS program is expected to begin in early 2010. The first three reviews suggest a need for a single strategic framework for Earth system research. Based on this need, and led by their new director, Dr. Deliang Chen, ICSU is leading a "visioning" process to develop a new vision and strategic framework for Earth system research. This process will begin in late 2009 and is expected to result in a single strategic framework for Earth system research by 2014.

International Human Dimensions Programme. The IHDP hosted its Seventh Open Science Meeting, "The Social Challenges of Global Change," 26-30 April 2009 in Bonn, Germany at the United Nations University campus. The meeting focused on four themes: demographic challenges with emphasis on health; challenges from limitations of resources/ecosystem services; social cohesion and equity; and adaptive institutions and governance. The IHDP community has grown over the past several years, with a broad spectrum of social scientists including economists, demographers, sociologists, and anthropologists represented. This Open Meeting also broke records for the IHDP with over 1,200 registered participants from 90 countries, 40% of whom were women and 40% of whom were from less-developed countries. The community clearly recognizes the importance of informing decisionmaking about adaptation and mitigation based on the incontrovertible evidence of ongoing and anticipated changes in the Earth system and will be responsive with the best possible science.

African Network on Earth System Science. Since its inception in 2005, AfricanNESS has developed a science plan that will serve as a roadmap for sustained regional global environmental change research in Africa. AfricanNESS, with the ICSU Regional Office for Africa and facilitated by IGBP, released a merged science plan in 2008. The merging of these science plans is the result of several years of parallel effort and significant community participation. It is hoped that the merged science plan will be widely accepted and implemented. Many challenges remain, but in those challenges lie significant opportunities to advance science globally. One challenge is finding ways to rebalance and develop research capacity. The science plan focused on four crosscutting areas: food and nutritional security, water resources, health, and ecosystem integrity. A significant number of global environmental change researchers currently in Africa could contribute to AfricaNESS projects.

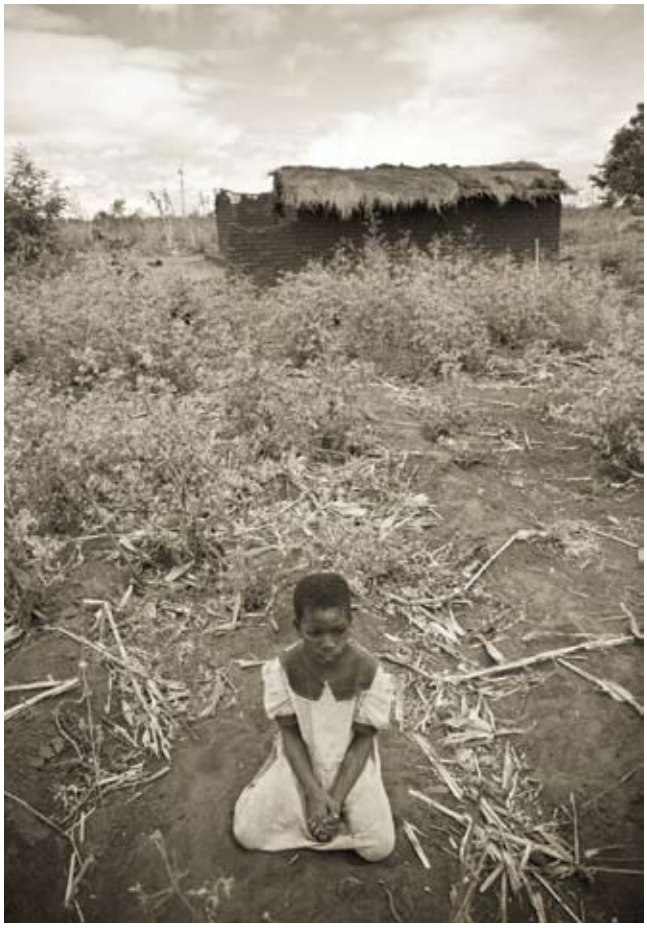
HIGHLIGHTS OF PLANS FOR FY 2010

DIVERSITAS. The DIVERSITAS program will continue with its four core projects aimed at further developing a comprehensive understanding of biodiversity and the interactions between biodiversity and global change. DIVERSITAS will hold its Second Open Science Conference, "Biodiversity and Society: Understanding connections, adapting to change," 13-16 October 2009 in Cape Town, South Africa. The meeting will be organized around the overarching themes of strengthening biodiversity science, supporting the science-policy interface, and integrated approached to topical issues.

DIVERSITAS also plans to implement a number of activities aimed at strengthening biodiversity science, including improving predictions of climate change impacts on biodiversity; developing tools for managing ecosystem services; understanding and predicting links between changes in biodiversity and human health; providing an evolutionary context to global change research; and building geo-referenced biological databases to improve understanding of biodiversity. DIVERSITAS will continue to develop the global biodiversity observing system GEO-BON. DIVERSITAS also will contribute to the CBD and the Conference of the Parties, the governing body of CBD that advances implementation of the Convention through decisions made at its periodic meetings.

Earth System Science Partnership. The CGIAR and ESSP Challenge Program "Climate Change, Agriculture and Food Security" will host its international launch in early 2010. The main goals of the program are to advance understanding of managing the tradeoffs between food security, livelihood, and environmental goals; to inform and develop options for agricultural development, food security policy, and investment strategy decisions with information about climate adaptation; and to assist stakeholders to adopt adaptive management practices in response to the changing climate. In 2009, the program will recruit a director for the program and theme leaders through a competitive, international process and identify and establish a secretariat.

SysTem for Analysis, Research, and Training. START will continue to promote research-driven capacity building with a variety of activities. These include activities aimed at biodiversity conservation



in Africa, continuation of the African Climate Change Fellowship Program, collaboration with the Stockholm Environment Instititute on building capacity for managing and adapting to climate change in Asia and Africa, climate change research and assessment activities that build on the success of the Assessments of Impacts and Adaptations to Climate Change (AIACC) project, and a collaborative project with WCRP and IHDP on Asian coastal megacities called "Cities at Risk." Regional work including the African Small Grants Program and several other capacity-building efforts will continue as well.

World Climate Research Programme. The WCRP, including all of its core projects, groups, and panels, will undergo a major planning effort in 2009 to establish a way forward for the program for the intermediate (2009-2013) and long term (2013 and beyond). The intermediate-term focus is in line with the Strategic Framework (2005-2015) and will be implemented through current projects and activities. WCRP modeling efforts will have a major focus on developing seamless prediction strategies (weather to long-term climate change). WCRP's new CORDEX

(Coordinated Regional climate Downscaling Experiment) initiative will improve coordination of international efforts in regional climate downscaling, from both dynamical and statistical methods, by defining a common set of regional domains and reporting formats. WCRP has also begun a series of new pan-WCRP activities focusing on specific research topics including climate extremes and decadal prediction science.

International Geosphere-Biosphere Programme.[9] The IGBP will begin a mid-term synthesis effort in 2009 and expects to host its next Open Science Conference in 2012. The IGBP anticipates making a substantial contribution to the IPCC Fifth Assessment report after the success of the Fourth Assessment Report in which 84 IGBP scientists were co-authors. IGBP has also initiated a fast track initiative "The State of the Earth 2030-2050" that will describe what conditions on Earth may be like during that period based on expert knowledge from a variety of disciplines. The IGBP has also been involved in a series of workshops dedicated to learning from the IPCC Fourth Assessment Report. The most recent of the workshops took place in Amsterdam in early 2009. The forthcoming report from the workshop should help define the role of the global change research programs in the Fifth Assessment Report.

CHAPTER REFERENCES AND ENDNOTES

[1]See <www.state.gov/documents/organization/109816.pdf>.

[2]For information on the bilateral climate partnerships, see <www.state.gov/g/oes/climate/>.

[3]For information on the climate change science and technology bilateral partnerships, see <www.climatescience.gov/Library/stratplan2003/final/ccspstratplan2003-chap15.htm#5>.

[4]See <diversitas-international.org>.

[5]See <www.imoseb.net/>.

[6]See <essp.org>.

[7]See <www.globalcarbonproject.org/carbonbudget/07/index.htm>.

[8]More about the visioning process may be found at <www.icsu.org/1_icsuinscience/ENVI_VIS_1.html>.

[9]See <igbp.net>.

APPENDIX A

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM PARTICIPATING AGENCIES

The following pages present information about the contributions to the USGCRP by each of the program's participating agencies:

- Department of Agriculture (USDA)
- Department of Commerce (DOC)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Health and Human Services (HHS)
- Department of the Interior (DOI)
- Department of State (DOS)
- Department of Transportation (DOT)
- Agency for International Development (USAID)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Smithsonian Institution (SI)

Principal areas of focus, program highlights for FY 2010, and related research are summarized for each agency.

U.S. DEPARTMENT OF AGRICULTURE

Agricultural Research Service (ARS)
Cooperative State Research, Education, and Extension Service (CSREES)
Economic Research Service (ERS)
Forest Service (FS)
Global Change Program Office (GCPO)
Natural Resources Conservation Service (NRCS)

Principal Areas of Focus

The U.S. Department of Agriculture (USDA) supports climate change science activities to empower farmers, foresters, ranchers, land owners, resource managers, policymakers, and Federal agencies with science-based knowledge to manage the risks and challenges of climate change and to reduce emissions of atmospheric greenhouse gases and enhance carbon sequestration. USDA conducts and sponsors a broad range of research that supports the USGCRP, focused on evaluating risk to natural resources, estimating the role of forestry and agricultural activities in greenhouse gas emissions and carbon sequestration, and developing practical management strategies and approaches to manage emissions and adapt to changes. USDA's research program seeks to determine the significance of terrestrial systems in the global carbon cycle; promotes the capture and use of methane emitted from livestock waste facilities for on-farm power generation; assesses the potential of bioenergy as a substitute for fossil fuels; identifies agricultural and forestry activities that can help reduce atmospheric greenhouse gas concentrations and increase carbon sequestration; quantifies the risks and benefits arising from environmental changes to agricultural lands and forests; and develops management practices that can adapt to the effects of global change, including potential beneficial and adverse effects.

Program Highlights for FY 2010

ARS climate change research contains two major components: 1) the development of technologies to reduce atmospheric greenhouse gas concentrations through management of agricultural emissions and carbon sequestration; and 2) the development of technologies that will enable agriculture to adapt to climate change for continued production of food, fiber, and biofuels, and stewardship of natural resources. A new five-year plan for this research was developed during 2008, and during 2009, individual research projects addressing the components were developed and peer review of the project plans was initiated. ARS greenhouse gas emissions research centers around the Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) project that is being conducted at 30 locations across the United States, measuring greenhouse gas emissions from multiple agricultural management systems, building a database, and formulating decision support for mitigation of emissions and optimization of carbon sequestration by producers and land managers as well as policymakers. Greenhouse gases under investigation include carbon dioxide, nitrous oxide, and methane. Crop, rangeland and pasture, and animal production systems are addressed. ARS research to enable agriculture to adapt to climate change includes understanding the responses of agricultural systems to anticipated climate change; understanding the impact of anticipated climate change on endemic and exotic pests, weeds, and diseases; evaluating and adapting agronomic management to climate change; and identifying and developing scalable methodologies for assessing potential impacts and adaptation of agriculture to climate change. The impact of precipitation and temperature changes, increasing near-surface ozone, and the fertilization effects of enhanced atmospheric carbon dioxide and their interactions are being investigated via laboratory and field experiments. The development of systems models using the experiment results provides the foundations for decision support tools to help producers, land managers, and policymakers respond to, and where possible, help agriculture benefit from projected climate changes. The ARS climate change research program is complemented by the ARS watershed and water availability research program with research on drought monitoring and water management technologies of importance to sustaining agricultural production and ecosystem services.

CSREES weather and climate projects focus on determining the effects of global change and climate on land-based systems and the global carbon cycle and on identifying agricultural and forestry activities that can help reduce greenhouse gas concentrations. Programs such as the UV-B Monitoring and Research Program strengthen the Nation's capacity to address critical environmental priorities and contribute to improved air, soil, and water quality; fish and wildlife management; enhanced aquatic and other ecosystems; the sustainable use and management of forests, rangelands, watersheds, and other renewable natural resources; and a better understanding of global climate change, including its impact on the diversity of plant and animal life. The agency supports research to determine the influence of irrigation practices and water management on carbon storage in land-based systems. Irrigation schedules and best practices are then communicated to stakeholders for implementation. Contributions from research programs include new tools for accurately measuring greenhouse gases, methods for measuring and estimating carbon in ecosystems at different scales, and effective ways to sustain productivity in a changing environment. To achieve a true holistic view of global change and climate impacts, research, education, and extension projects occur in an integrated manner. For example, mitigation steps to reduce carbon dioxide or methane emissions are taught to industry professionals and education specialists to achieve national goals of greenhouse gas reductions. This type of thinking brings together the natural sciences, engineering, mathematics, business, social and political sciences, economics, and education to achieve a system science view of agricultural and forestry production and sustainability. This approach provides reliable knowledge for decisionmaking processes at regional and national levels. Global change extension programs focus on 1) technologies and practices to reduce carbon in the atmosphere and 2) risk management practices to anticipate natural and human impacts on agricultural ecosystem dynamics. Education and extension activities provide robust scientific information for learning and decision support systems for citizens and public officials to evaluate the environmental and socioeconomic impacts of policy options for sustainable resource management.

ERS is a primary source of economic information and research for USDA. ERS' climate change research program is engaged in predicting responses of farmers to greenhouse gas mitigation options and analyzing the impact of mitigation options on domestic and global land and water use. This program includes assessing how the rapid increase in grain-based ethanol production and the potential use of cellulosic materials as an ethanol feedstock will affect agricultural markets, consumer prices, and environmental quality, and is expanding to include the effects on domestic and global land use and greenhouse gases, including economic and environmental tradeoffs. ERS is developing models and analytical capacity to examine the potential economic implications of farmers' participation in voluntary carbon offset markets of varying design, including soil and nutrient management practices and methane destruction from manure management. ERS intends to look into the benefits and costs of development and uptake of technologies that can facilitate adaptation by farmers to weather conditions that may be more variable, hotter, and dryer. ERS is also looking into whether and to what extent commodity production, prices, and trade will be affected by adaptation to a new climate regime.

FS research is concentrated on three areas. First, mitigation research aims to increase the fossil fuel carbon removed from the atmosphere by forests and by offsets to fossil fuels provided by forest products. Second, adaptation research aims to reduce emissions of forest carbon from major disturbances by developing and evaluating methods to increase ecosystem resilience to current and future climate stresses on forests and rangelands, also thereby maintaining ecosystem health and services (e.g., timber, water supplies, biodiversity). Third, creation of decision support systems—including monitoring, reporting, and synthesis of information—supports land managers and policymakers in adopting these new research results for optimum management of forests and rangelands in a changing environment. Within these three areas, FS research works at (i) expanding understanding of the global carbon cycle in forest and rangeland ecosystems, and the consequences of and feedback from the management and use of these ecosystems as they interact with the atmosphere; (ii) improving accuracy and ease of analyses of U.S. forest carbon inventory, and other monitoring and analysis systems for carbon dioxide; (iii) enhancing understanding of climate change impacts on forest health, major disturbance regimes, and ecosystem services; (iv) integrating observation and monitoring networks with process studies to better understand, forecast, and manage relationships between forest and rangelands and climate; (v) accelerating the development of manage-

ment technologies to increase carbon sequestration, provide fossil fuel offsets, enhance forest productivity, and maintain environmental quality; and (vi) providing integrated prediction models of forest dynamics under expected future changes in climate and atmospheric chemistry.

NRCS provides technical and financial assistance, programs, and incentives to enable producers to best manage private agricultural lands. Climate change is an overarching theme that cuts across NRCS activities. Greenhouse gas emission reductions are encouraged by NRCS' conservation programs, such as the Conservation Stewardship Program, Wetlands Reserve Program, Wildlife Habitat Incentives Program, Environmental Quality Incentives Program, Grassland Reserve Program, and Conservation Innovation Grants. NRCS has developed an online curriculum to train employees in issues related to air quality, energy, and climate change. NRCS maintains online fact sheets that help inform the larger public about the relationship between NRCS programs and climate change, including opportunities associated with carbon sequestration and environmental credit trading. The Carbon Management Evaluation Tool-Voluntary Reporting (COMET-VR) is an online interactive management tool providing a simple and reliable method for estimating changes in greenhouse gas fluxes resulting from changes in practices that alter soil carbon sequestration and fuel and fertilizer use. This and other tools provide producers with scientifically based technical information to inform decisions for their operations.

Related Research

USDA remains active in the Climate Change Technology Program (CCTP) and related efforts. The Global Change Program Office, FS, NRCS, ARS, CSREES, Farm Services Agency, and Rural Development mission area support improved measurement and accounting of greenhouse gases from agriculture, forestry, and grassland systems, as well as energy initiatives and renewable energy systems including biofuels and biomass-related research and development. Thirteen USDA agencies have been active in helping draft a strategic plan for USDA climate change science, and the plan's goals related to effects, adaptation, mitigation, and decision support have undergone public review. In addition, NRCS and FS are developing new measurement technologies, analytical techniques, and information management systems related to spatial carbon distributions. USDA continues to develop long-term data sets on land use, resource conditions, and climate through the National Resources Inventory, the Forest Inventory and Analysis Program, the Soil Climate Analysis Network, and the Snowpack Telemetry system to support understanding of climate-related changes in land resources. These networks provide critical data on the status and condition of land use in the United States in support of USGCRP research.

DEPARTMENT OF COMMERCE

Principal Areas of Focus

The National Oceanic and Atmospheric Administration (NOAA) and the National Institute of Standards and Technology (NIST) comprise the Department of Commerce contribution to the USGCRP.

NOAA's climate mission is to "understand climate variability and change to enhance society's ability to plan and respond." This is an end-to-end endeavor with the overall objectives of providing decisionmakers with a predictive understanding of the climate and communicating climate information so that the public can incorporate it into their decisions. These outcomes are achieved through implementation of a global observing system, focused research to understand key climate processes, improved modeling capabilities, and the development and delivery of climate information services. NOAA aims to achieve its climate mission and outcomes through the following objectives:

- Describe and understand the state of the climate system through integrated observations, monitoring, and data management
- Understand and predict climate variability and change from weeks to decades to a century
- Improve the ability of society to plan for and respond to climate variability and change.

NOAA relies on its Federal, academic, private, and international partners to achieve its objectives. These objectives are implemented through three distinct, yet integrated, programs: Climate Observation and Monitoring, Climate Research and Modeling, and Climate Services Development.

NIST, through its Climate Change Program, provides the measurement science and standards to help ensure the accuracy, reliability and compatibility of climate and greenhouse gas observations, which underpin climate-model predictions and policy decisions. The two current thrusts within the Climate Change Program at NIST are Greenhouse Gas Measurements and Climate Science.

Program Highlights for FY 2010

National Oceanic and Atmospheric Administration

Climate Observation and Monitoring

The Climate Observation and Monitoring Program develops and sustains integrated atmospheric, oceanic, and Arctic observation networks, primarily *in situ*, and maintains consistent and long-term archives of and access to historical climate data. Examples of NOAA observation networks include the U.S. Climate Reference Network and the carbon dioxide (CO_2) baseline observatories, including the Mauna Loa and South Pole stations. NOAA routinely provides climatological information, such as basic statistics and extremes, based upon extended records usually greater than 30 years in length. The program has two basic capabilities: observations (atmosphere, oceans, and forcing), and data management and information. These capabilities taken together increase the value and utility of both *in situ* and satellite observations, improve the performance of models, and reduce the uncertainty of predictions. The program contributes to the national and global objectives outlined in the *2003 Strategic Plan*, as well as NOAA's Strategic Plan, the Strategic Plan for the U.S. Integrated Earth Observation System (IEOS), and the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan.

Activities in FY 2010 will:

- Create a scientific data stewardship plan to generate, analyze, and archive data from climate satellite sensors in long-term climate data records
- Maintain the Global Ocean Observing System (GOOS)
  - Continue technology refreshment to replace obsolete components of the Tropical Atmo sphere Ocean Array, a critical El Niño-Southern Oscillation observing system
  - Implement long-term monitoring of ocean acidification for assessing climate change impacts on living marine resources
- Maintain the contiguous U.S. Climate Reference Network, continue the installation of soil moisture sensors at 114 stations in support of the National Integrated Drought Information System, and expand the Network in Alaska
- Continue to re-measure key ocean properties along cross-sections of the world's oceans via the Repeat Hydrography Program
- Continue to maintain and update Carbon Tracker, the combined measurement and modeling system that keeps track of the emissions ("sources") and removal ("sinks") of atmospheric CO_2 globally
- Integrate the North American Carbon Program and relevant aspects of the Ocean Carbon and Climate Change Program to better quantify and understand the carbon budget of North America and adjacent ocean basins, including terrestrial, freshwater, oceanic, and atmospheric sources and sinks that influence atmospheric CO_2 and methane (CH_4)
- Implement the National Climate Model Portal to generate and house model-based data records and provide archives of and access to high-resolution weather and climate reanalysis datasets

Climate Research and Modeling

The Climate Research and Modeling program develops and improves NOAA's capability to make predictions of climate on time scales leading up to several decades, and conducts research to improve understanding of changes in atmospheric composition and past and present climate in order to make decadal- to centennial-scale projections of future climate at global to regional scales. The program maintains and implements real-time climate monitoring data sets and the next-generation suite of operational climate products and assessments, incorporating improvements in climate models and forecast generation techniques. The program also develops estimates of changes in atmospheric composition (including atmospheric chemistry, carbon, and other biogeochemical cycles) and future changes in climate forcing agents. In addition, the program maintains and develops leading-edge Earth System Models for the understanding of past climate change, interpretation of present climate events and trends, and projection of future climate change at global to regional scales.

The Climate Research and Modeling program is organized into three mutually reinforcing capabilities: understanding climate processes; Earth system modeling, predictions, and projections; and climate analysis and attribution. Activities are spread

across several offices within NOAA and NOAA laboratories, and leverage an extensive array of peer-reviewed, university-based competitive research.

This program provides the Nation with a suite of environmental forecasts and projections on time scales up to centennial and at spatial scales from regional to global. The program helps regional and national resource managers to better plan for the impacts of climate variability and change and provides scientifically rigorous, objective climate change assessments to support policy decisions.

Activities in FY 2010:

- Make strategic use of expanded high-performance computing resources to address gaps in climate modeling for continuing research into the causes and impacts of climate change, including abrupt climate change, and investigate options for mitigating climate change and its impacts.
- Conduct initial model simulations for use in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5), including with NOAA's new coupled climate model, with a newly developed Earth System Model that simulates the global carbon cycle, and with a prototype decadal prediction system with data assimilation capability that will be used to assess potential climate predictability on decadal scales.
- Continue investigation of the effects of natural and anthropogenic forcings, and feedback mechanisms, on climate at global to regional scales.
- Continue development of and conduct simulations with new 25-, 50-, and 100-km grid atmospheric models for studies of regional climate changes including the link between hurricanes and climate change and the causality of recent droughts.
- Investigate biogeochemical-climate interactions using Earth System Model simulations, including feedbacks involving the marine and terrestrial carbon cycles and the physical climate system.
- Analyze results from activities conducted as part of the International Polar Year in FY 2008 and FY 2009, including a study of aerosol properties and atmospheric chemistry over the Arctic.
- Conduct diagnostic studies of 20th-century climate with development and distribution of derived products.
- Continue to provide an operational testing environment to accelerate improvements in operational climate models and associated climate forecast products and applications, especially for drought and regionally specific climate applications.
- Continue studies on the linkages between climate and air quality and develop estimates of aerosol-cloud interactions for use in IPCC AR5 assessment activities.
- Provide climate models and prototype forecasts and/or projections to climate assessment reports and key stakeholders to inform resource management and policy decisionmaking.

Climate Services Development

The Climate Services Development (CSD) Program assesses the impacts of climate variability and change, supports regional and sectoral adaptation activities, and develops climate information products and tools appropriate for evolving user needs. The program supports decisionmakers through a variety of mechanisms such as development of new tools and methodologies to enable decisionmakers to better incorporate climate forecasts into management decisions involving key socioeconomic sectors and regions that are sensitive to impacts from weather and climate. This focus includes annual losses from droughts and floods, heat and cold waves, the positive and negative impacts of El Niño and La Niña events, sea level rise, and other high-impact climate events. The program also supports outreach activities such as participation in workshops and publications of CSD-funded research to expand understanding and appreciation of the challenges and opportunities that climate variability and change represent. The information developed by CSD utilizes observations, monitoring, analysis, modeling, forecasts, assessments, supporting data sets, and stakeholder-driven research and applications.

The CSD Program is organized under the following two capabilities: Assessing Climate, Impacts, and Adaptation and Climate Services Development and Delivery. CSD relies on NOAA's extensive infrastructure, collaborating with more than 150 offices at the national, regional, and local levels, as well as their partners working at the international, national, regional, State, and local levels.

The CSD Program is addressing an increased demand for traditional climate services, such as data and forecast dissemination and customer support, as well as identifying and satisfying new requirements for information on long-term climate trends; linkages between climate variability, climate change, and weather extremes; assessments of vulnerability;

and decision support in sectors such as drought and water management, fire, emergency preparedness, health, transportation, energy, coastal, urban, and ecosystem management.

Activities in FY 2010 will:

- Develop decision support tools, such as climate-fisheries models and web-based climate-agriculture tools
- Increase the understanding of regional climate impacts through basic and applied research and diagnostic and modeling studies
- Develop—through the Sectoral Applications Research Program—comprehensive requirements, methodologies, and decision support tools focused on sea level rise, extreme events and community planning, climate and integrated ecosystem management, climate extension services in coastal regions, and climate and urban drainage systems
- Continue—through the Regional Integrated Sciences and Assessments Program—to enhance integration of regional programs with applied research capabilities to strengthen end-to-end development and provision of climate information services
- Continue to develop the National Integrated Drought Information System
  - Continue development of the U.S. Drought Portal in conjunction with Federal partners (USGS, NASA, and USDA) and non-Federal partners (Drought Mitigation Center and the Earth Systems Integrated Enterprise)
  - Continue development of the next-generation Climate Forecast System (CFS) and of a multi-model ensemble prediction system using CFS to accelerate the transition of research advances to new and improved objective drought-monitoring and prediction products
  - Implement early-warning system development projects for different water, energy, agricultur al, ecosystem management, and drought condi tions at varying geographical resolutions.

National Institute of Standards and Technology

Greenhouse Gas Measurements

NIST plays a crucial role in developing the measurement science and standards that ensure the accuracy and comparability of quantitative measurements of greenhouse gas sources and sinks. Any mitigation effort will require the accurate, reliable and consistent measurement and monitoring of greenhouse gases both at the point of origin and remotely to assess current greenhouse gas baselines, verify greenhouse gas emissions, measure absorption of greenhouse gases (sinks), and enable the accurate determination of a greenhouse gas limit or cap. Within its Greenhouse Gas Measurement program, NIST is addressing the multiple measurement challenges to ensure the immediate development and implementation of a robust greenhouse gas mitigation program within the United States, and the long term measurement needs to ensure that mitigation targets are successful. In FY10, activities in Greenhouse Gas Measurements include:

- Develop and validate new measurement methods and standards for quantitative and traceable greenhouse gas monitoring that are critical to implementing a U.S. mitigation strategy.
- Develop a NIST Smokestack Monitoring of Emissions Test and Calibration Platform (METCaP) as a test bed to demonstrate new emissions monitoring instrumentation protocols, methodologies and usage. (This effort will help ensure the quality of third-party emission measurements.)
- Initiate a demonstration project, over a sufficiently sized geographical area, to harmonize local greenhouse gas inventory measurements with global remote sensing measurements and modeling. Harmonization of these two types of measurements is critical to assessing the success of mitigation efforts.

Climate Science

The second thrust of NIST's Climate Change Program is the measurement research for Climate Science. As part of a broad national and international effort, NIST plays a crucial role in climate science by helping establish the national and international standards that ensure that measurements of the small changes in climate are accurate and comparable over many decades, in many different places, and using many different technologies. The Climate Science program at NIST focuses on the measurement science aspects of monitoring, modeling and predicting changes to the Earth's climate, where the ability to measure and understand small rates of change in climate variables is critical to developing sound policies. In FY10, activities in Climate Science will:

- Develop the measurement science to advance our understanding of the optical properties of aerosols, key to accurately quantifying the albedo of the Earth's atmosphere in climate models.
- Develop improved methods for measuring

near-infrared to ultra-violet atmospheric transmittance.
- Develop and characterize calibration laboratory sources of microwave, infrared, and visible radiation used in the prelaunch and on-orbit calibration of sensors. These capabilities support measurements made by NOAA or USGS operational satellite programs, such as NPOESS, GOES-R, LDCD, as well as NASA research satellites.

DEPARTMENT OF DEFENSE

Principal Areas of Focus

The Department of Defense (DOD) environmental research programs have a specific goal of addressing global climate change impacts that directly address DoD assets and its national security mission. DoD continues a history of participation in the USGCRP through sponsored research that concurrently satisfies both the national security requirements and the goals of the USGCRP. All data and scientific results obtained using DOD research funds are routinely made available to the civil science community. DOD science and technology investments are coordinated and reviewed by the Office of the Secretary of Defense and the individual research agencies—the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), and the Defense Advanced Research Projects Agency (DARPA). Research explicitly directed toward these issues is funded out of the Strategic Environmental Research and Development Program and the Army Corps of Engineers research activities. Together they have the responsibility to jointly develop the DOD Basic Research Plan (BRP), which undergoes a biennial program review by a panel of experts from universities, industry, and nonprofit research institutions (Defense Basic Research Review). As the performance of DOD systems, platforms, and operations may be influenced by natural environmental conditions, understanding the variability in the Earth's environment is of interest to many DOD science programs. Much of the research performed under the ONR's Operational Environments focus area and the ARO's Environmental Sciences Division, for example, lead to fundamental understanding of physical processes that are of particular relevance to the USGCRP.

In May 2009, the Navy formed a Task Force on Climate Change to advise the Chief of Naval Operations on the impact of climate change on future Navy and Marine Corps operations. The objectives are to provide a central clearing point for climate change information and to assess potential impacts. Most importantly, the Task Force is to provide information about critical time lines relative to allocation of resources required to adapt to the future. The role of the task force is to address the impacts of climate change but this may ultimately result in additional research relative to mitigation and adaptation. The budgetary impact, however, is most likely to be in FY 2011 or later.

Program Highlights for FY 2010

Global Observations and Models

The Navy is a principal member of the National Oceanographic Partnership Program (NOPP), a broad consortium of agencies that collaborate in the development and demonstration of integrated ocean observations systems, data management systems, and real-time coastal, basin-scale, and global ocean prediction systems. Via NOPP, the ONR funds ongoing development of the Hybrid Coordinate Ocean Model (HYCOM), a predictive model that runs efficiently in parallel computing environments and includes sophisticated techniques for the assimilation of satellite and *in situ* observations. The Navy supports an associated data server project to develop and demonstrate a comprehensive data management and distribution strategy that allows easy and efficient access to HYCOM-based ocean predictions for coastal and regional users, as well as making them available to the wider oceanographic and scientific community, including climate and ecosystem researchers, students, and the general public.

The ONR also supports a number of basic research programs that, while directed toward fulfilling the objectives outlined in the Naval Science and Technology Strategic Plan (available at <www.onr.navy.mil>), also support the science goals of the USGCRP.

Within the "Operational Environments" focus area, ONR incorporates both observational and modeling elements into major field programs designed to learn more about the underlying physics of the ocean and atmosphere. The development of new sensors, sensing platforms, and sensing strategies is supported in order to achieve these goals, and ongoing research into predictive systems for the ocean and atmosphere is supported, with the primary goal of improving environmental forecasts for DOD. Most of this basic research enhances fundamental understanding of the dynamics of the coupled ocean-atmosphere system, and is thus relevant to climate change issues. As one example, a recent outcome of the program is a new coupled ocean-wave-atmosphere model for hurricanes that shows significant promise in improving forecasts of storm intensity. This work continues in FY 2010 under two initiatives that explore the generation of tropical cyclones and their impact on the thermal structure of the upper ocean. The research may lead to a better representation of these systems in climate simulations and improved understanding of the sensitivity of these high-impact weather events to climate change.

Polar Regions Research

The *2003 Strategic Plan* identifies plans to increase observations of the polar atmosphere, ice, and ocean environment, as they have exhibited more rapid changes than the lower latitudes. Of particular interest to the DOD is the observation, understanding, and prediction of diminished Arctic sea ice cover, such that the military may respond in a manner consistent with any emerging national security issues. The U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) actively investigates the impacts of climate trends for USACE, Army, DOD, and other agencies. The CRREL research program responds to the needs of the military, but much of the research also benefits the civilian sector and is funded by non-military customers such as NSF, NOAA, NASA, DOE, and State governments. Satellite data show a downward trend in the summer extent of Arctic sea ice in recent years, and the sonar data collected by U.S. Navy submarines in the Arctic between 1957 and 2000 show that the average ice thickness has decreased between 33 and 42%. CRREL applies science and engineering research to address climate impacts for DOD and other Federal and State agencies, and through cooperative agreements with academic institutions and private industry.

The Navy, again through ONR participation in NOPP, has been funding research related to climate change under the "Coastal Effects of a Diminished-Ice Arctic Ocean" program. The efforts wrapping up in FY 2010 have explored ocean observing system strategies for the Alaska Beaufort and Chukchi Seas, changes in the circulation and wave dynamics of the coastal Arctic, the impact of climate variability on coastal production and transport of sediment, and the measurement and prediction of seasonal changes in sea ice cover in the Beaufort and Chukchi Seas.

Satellite Sensors and Observations

Via the Air Force, the DOD continues to fund 50% of costs related to the National Polar-Orbiting Operational Environmental Satellite System (NPOESS)—a result of the convergence of national sensing suites. NPOESS will monitor global environmental conditions and collect and disseminate data related to the weather, atmosphere, oceans, land, and near-space environment. The NPOESS Program is managed by the tri-agency Integrated Program Office run by the Department of Commerce, DOD, and NASA.

Related Research

Other DOD-sponsored research and supporting infrastructure also contribute to observing, understanding, and predicting environmental processes related to global change. Associated research programs include theoretical studies and observations of solar phenomena, monitoring and modeling of unique features in the middle and upper atmosphere, terrestrial and marine environmental quality research, alternative energy generation, and energy conservation measures. The DOD's continued investment in environmental research infrastructure—such as the Navy's procurement of two new ocean-going research vessels for the University-National Oceanographic Laboratory System (UNOLS) fleet, scheduled for delivery in 2014, and the various services' operational oceanographic and meteorological computational centers—will continue to provide data and services useful to the scientific community and the USGCRP.

DEPARTMENT OF ENERGY

Principal Areas of Focus

Research supported by the Department of Energy (DOE) Office of Science focuses on the effects of energy production and use on the global climate system. The research seeks to understand the regional and global climate response to changes in greenhouse gas and aerosol concentrations. Research covers five focus areas: 1) Climate Change Process Research, 2) Climate Change Modeling, 3) Climate Change Ecological Effects, 4) Carbon Sequestration Research, and 5) Climate Change Education and Infrastructure.

Program Highlights for FY 2010

DOE will enhance and continue support of climate change research at its National Laboratories and other public and private research institutions, including universities. In support of the USGCRP, the DOE Office of Science's Climate Change Research Program will continue to support climate change research that is generating the scientific knowledgebase needed to: (1) inform the public discussion about climate change; (2) support scientific considerations of energy policy options related to climate change; and (3) provide the scientific foundations and tools that can be used by the Nation to plan for, adapt to, and mitigate climate change.

Climate Change Process

Collection and analysis of data from DOE's Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) sites will continue in FY 2010 to improve understanding of the radiative transfer processes in the atmosphere and to formulate better parameterizations of these processes, especially cloud and aerosol effects, for use in climate models. In FY 2010, ACRF will conduct four field experiments to study various cloud types—cirrus, marine, and mixed-phase (ice and water)—to improve climate change models. A campaign at the North Slope of Alaska site will be the first experiment to capture a full atmospheric profile of *in situ* cloud microphysics, aerosols, and radiative measurements during the Arctic transition season. A campaign at the Southern Great Plains site will address outstanding questions regarding mid-latitude cirrus properties and processes. The first mobile facility will be deployed to study low marine clouds and aerosols in the Azores. The second mobile facility will study liquid and mixed-phase clouds in Colorado. These measurements support research efforts designed to address the largest uncertainties in the climate models. ACRF will also conduct a multi-agency field campaign in California to study carbonaceous aerosol formation in a region affected by biogenic and human emission sources.

In FY 2010, DOE research will continue to focus on improving the understanding of the relationship of clouds and radiative transfer processes in the atmosphere and the characterization of aerosol physical, chemical, and optical properties and their effects on the Earth's energy balance. Research will focus on furthering our understanding of the life cycle of marine boundary layer clouds and their impacts on radiation. DOE's priority aerosol studies include transformations and properties of carbonaceous aerosols, especially secondary organic aerosols, that are poorly predicted by current atmospheric models. The research will also focus on aerosol processes controlling new particle formation and growth, as well as the properties that affect their activation as droplet and crystal nuclei. Research will use atmospheric measurements from laboratory, ACRF, and other sources in this effort. Research will also be coordinated with Earth System Modeling to quickly and effectively incorporate results into climate models.

Climate Change Modeling

DOE will enhance climate-modeling research to develop, improve, evaluate, and apply fully coupled atmosphere-ocean-sea ice-land surface general circulation models (GCMs) that simulate climatic variability and change over decadal to centennial time scales and that simulate regional climate variability and change with greater fidelity. DOE will continue projects initiated in FY 2009; these projects focus on abrupt climate change and on incorporation and testing of various aerosol schemes, convection schemes, ice sheets, and land-surface schemes in coupled models, and model evaluation using innovative metrics that span a variety of

climate time scales. DOE will also enhance research for developing regional modeling capabilities.

DOE's Scientific Discovery through Advanced Computing (SciDAC) for Climate Change Research will continue partnerships with the Advanced Scientific Computing Research program, including work toward the creation of a first-generation Earth System Model based on the Community Climate System Model that treats the coupling between the physical, chemical, and biogeochemical processes in the climate system. The model will include comprehensive treatments of the processes governing well-mixed greenhouse gases, natural and anthropogenic aerosols, the aerosol indirect effect, and tropospheric ozone for climate change studies. Research will develop and test a global cloud-resolving model using a geodesic grid, with grid-cell spacing of approximately 3 km, capable of simulating the circulation associated with large convective clouds.

Climate change information is being increasingly sought for impact studies and national and international assessments. These activities are at the interface of process research and global climate modeling, and are expected to accelerate process representation in coupled Earth system models for climate change projections. The DOE leadership class computational facilities now provide computing resources for models to be run at resolutions for which complex issues of data archiving, management, and dissemination need to be addressed. DOE will develop such tools and capability.

The Integrated Assessment of Global Climate Change Research Program will continue to support research on the nature and magnitude of human-Earth systems interactions, providing scientific insights into the integrated drivers of climate change and the impacts of and adaptations to those changes. The program will deliver improved science-based tools for determining safe levels of greenhouse gas emissions and understanding of the relative efficiencies and impacts of potential mitigation strategies. Consistent with recommendations by the Biological and Environmental Research Advisory Committee, the research will undergo a transformation and will shift considerable attention to the challenge of representing climate change impacts and adaptations within integrated assessment models. Development of non-monetary valuation and visualization methods and tools will be an important dimension of this new work. Additionally, DOE will explore the application of more advanced computational platforms reflecting the need for tighter coupling between what are presently reduced-form models and the rich detail and reduced uncertainty of underlying biogeophysical models.

Climate Change Ecological Effects

DOE will continue to improve understanding of the role of terrestrial ecosystems in the global carbon cycle, with attention to processes that control the rate of carbon dioxide (CO_2) exchange with ecosystems and that affect the rate of atmospheric increase and climate forcing by this greenhouse gas. DOE research will continue to contribute to the North American Carbon Program (NACP) through support of experiments, observations, and modeling of atmospheric CO_2 and the terrestrial carbon cycle. Research will continue to focus on the AmeriFlux network of observations, experiments, modeling, and syntheses. As part of joint carbon cycle-climate change research to improve simulation models, DOE will provide information on biogeochemical and physiological responses and terrestrial ecosystem feedbacks related to climate change in several mid-latitude ecosystems of North America.

In FY 2010, DOE will continue to sponsor experimental studies of the potential effects of warming and changes in precipitation on multiple terrestrial ecosystems. The new scientific data and understanding obtained by this research will facilitate informed decisionmaking about the means of producing the energy needed by society. It will do this by defining relationships between climatic changes that might be caused by energy production and the potential effects of those changes on the health of terrestrial ecosystems, and the organisms that they contain. In particular, experiments will determine linkages between warming and the possibility of species migrations, the expansion of species into areas that are presently too cool for their success, and the decline of species or ecosystems presently at the warm edge of their ranges. Field experiments will be conducted in high-elevation forests and meadows associated with the alpine tree line, the transition zone (ecotone) between temperate and boreal forests, and western shrubland. In addition to field experiments, laboratory experiments will determine relationships between warming and the success of plants and animals in model ecosystems. Laboratory studies will focus on key testable hypotheses about ecological effects of warming.

In FY 2010, DOE expects to begin design and development of the "next-generation" ecosystem-climate change experiments in terrestrial ecosystems. The experiments are expected to address critical knowledge gaps concerning effects of multiple factors (e.g., rising temperature in combination with elevated CO_2 concentration) on the structure and functioning of ecosystems, including potential feedbacks from terrestrial ecosystems to climatic change. The experiments will include a focus on nonlinear and threshold responses of ecosystems to climate change variables.

Carbon Sequestration Research

DOE plays a major role in carbon sequestration research to reduce atmospheric concentrations of energy-related greenhouse gases, especially CO_2, and their net emissions to the atmosphere. The research focuses on both developing the scientific information needed to enhance the natural sequestration of excess atmospheric CO_2 in terrestrial systems, and assessing the potential environmental consequences and ancillary benefits of that enhanced sequestration. It also includes research to develop biological approaches for sequestering carbon either before or after it is emitted to the atmosphere. Funding for DOE's carbon sequestration research is part of the Climate Change Technology Program (CCTP). CCTP also provides related research funding to support a balanced and diversified portfolio of advanced technology research and development, focusing on energy efficiency enhancements; low greenhouse gas emission energy supply technologies; carbon capture, storage, and sequestration; and technologies to reduce emissions of non-CO_2 gases. Together, the USGCRP and CCTP will help lay the foundation for future progress. Advances in the climate change sciences under the USGCRP are expected to improve understanding about climate change and its impacts. Similarly, advances in climate change technology mitigation under CCTP are expected to bring forth an expanded array of advanced technology options at a lower cost, which will help reduce greenhouse gas emissions.

Climate Change Education and Infrastructure

DOE will also continue support of its Global Change Education Program in FY 2010, including support of undergraduate and graduate students through the DOE Summer Undergraduate Research Experience (SURE) and the DOE Graduate Research Environmental Fellowships (GREFs).

Support will also be continued for the Carbon Dioxide Information and Analysis Center (CDIAC). Data holdings include records of the concentrations of atmospheric CO_2 and other greenhouse gases; the role of the terrestrial biosphere and the oceans in biogeochemical cycles of greenhouse gases; emissions of CO_2 to the atmosphere; long-term climate trends; the effects of elevated CO_2 on vegetation; and the vulnerability of coastal areas to rising sea level. Data management support for major projects, such as the AmeriFlux network, measurements of CO_2 taken aboard ocean research vessels, and DOE-supported Free-Air CO_2 Enrichment (FACE) experiments, are also included.

DEPARTMENT OF HEALTH AND HUMAN SERVICES

National Institutes of Health
Centers for Disease Control and Prevention

Principal Areas of Focus

The Department of Health and Human Services (HHS) supports a broad portfolio of research related to environmental health and the health effects of global change. The National Institutes of Health (NIH) supports USGCRP research on the health effects of air pollution and temperature, water quality and quantity, infectious disease transmission, and materials used in new technologies to mitigate or adapt to climate change. In addition, the Centers for Disease Control and Prevention (CDC) is engaged in a number of activities related to climate change, such as emerging and reemerging infectious diseases. Such related research is growing in importance.

Research and Training Related to Climate Change

Researchers, clinicians, and public health officials are becoming alerted to the dynamic relationship between climate changes and human health. Some of these changes are readily apparent, while others are more subtle and require additional studies. Many

avenues of research and training currently funded by NIH are relevant to these public health concerns.

- Higher temperatures are likely to increase tropospheric ozone concentrations that contribute to cardiovascular and pulmonary illness. The NIH supports grants and intramural projects that investigate the effects of air pollution on respiratory disease, cardiovascular disease, and neurological disorders through basic and clinical research. Examples of research include projects that investigate the link between exposure to hazardous air pollutants and childhood cancer using spatial epidemiological models, the impacts of tropospheric ozone exposure on lung development, and the impacts of air pollution on asthma in children with the goal of identifying risk factors and guiding prevention.
- Climate change is likely to affect water quality and the distribution of toxicants. Droughts and floods can produce catastrophic sanitation problems as well as mold and chemical exposures such as those seen with Hurricane Katrina in 2005. Long-term toxicity and carcinogenicity due to mobilized chemicals in agricultural soils and drinking waters may also occur. The NIH supports research on exposure to agricultural chemicals and environmental toxicants. Examples of research include long-term prospective studies of potential health effects associated with exposure to pesticides and other agricultural exposures among farmers and their families, research on the effects of mold and other indoor allergens on children with asthma in post-Katrina New Orleans, and studies of human genetic susceptibility to carcinogens and toxicants.
- The ranges of vector-borne and zoonotic pathogens and the transmission of food- and water-borne pathogens are likely to be affected by climate change. The NIH supports research on infectious diseases, including the effects of climate change on the geographic distribution of pathogens. Examples include characterizing the genetics, population biology, ecology, and transmission dynamics of vector-borne diseases such as malaria and hantavirus, and investigating the distribution of microbial pathogens in coastal waters.
- Climate change models project that extreme heat events, or heat waves, will become more frequent and intense, and such events will have a major impact on areas and populations that are not well adapted to them. Increased mortality is a common feature of heat waves, particularly among the elderly. Many of these deaths are related to cardiovascular, cerebrovascular, and respiratory causes. The NIH supports research on the physiological mechanisms associated with heat stress. Examples of research include projects that investigate the impact of heat stress on circulatory control.
- Natural disasters, such as heat waves, hurricanes, droughts, and floods projected by climate change models, also take a toll on mental health. The NIH supports research on the impacts of natural disasters on mortality, family disruption, and physical and mental health. Research includes several projects that focus on mental health and substance use following Hurricane Katrina in 2005.

Most of NIH's work in this arena comprises studies that focus on the basic human biology of climate-sensitive conditions—health outcomes that are affected either by direct climate change itself or by adaptation or mitigation strategies. Such biomedical research is valuable in the development and evaluation of clinical and public health strategies to minimize the impacts of climate change on health.

NIH Challenge Grants in Health and Science Research

The NIH has recently taken steps to increase support for research on the health effects of climate change. As part of the American Recovery and Reinvestment Act of 2009, NIH has developed a new initiative called the NIH Challenge Grants in Health and Science Research. Included in the range of Challenge Topics that the NIH plans to support is research that focuses on the development of models to predict the health effects of climate change. Quantitative and predictive models of effects of climate change on disease burden and health outcomes are needed to facilitate public health planning and inform adaptation strategies. Of particular interest are studies that quantify the current impacts of climate on a diversity of communicable or non-communicable diseases, and studies that project the impacts of different climate and socioeconomic scenarios on health.

Health Effects of Climate Change Mitigation

In addition, the NIH is supporting research focused on the health effects of climate change mitigation strategies (e.g., global shifts in energy production and use that are intended to mitigate carbon dioxide production). The National Institute of Environmental Health Sciences is supporting The Wellcome Trust in its project that aims to describe and quantify the

population health consequences (both positive and negative) of key policy choices aimed at climate change mitigation in each of four sectors: energy, housing/built environment, transport, and food and agriculture.

Related Research

CDC conducts public health research on a wide variety of topics that are associated with climate change, ranging from vector-borne diseases to human health effects of heat waves. CDC has established a long-term national surveillance system to monitor enzootic transmission activity and patterns across the entire country. For West Nile virus (WNV), the agency is conducting research on the potential human health burdens and transmission characteristics of the disease in Guatemala to study the ecology of WNV and other arboviruses causing encephalitis. The results of the ecology studies may lead to a better understanding of how climate change may influence transmission dynamics. CDC is conducting interrelated investigations of the complex ecology of WNV to better understand its distribution in the United States. Scientists from CDC are working with colleagues from around the world to analyze the key climatic variables and other ecological factors that influence the transmission and distribution of other zoonotic diseases including Chikungunya viral fever, Japanese encephalitis, Rift Valley Fever, and plague. Researchers are developing mathematical models that relate changing weather conditions, among other factors, to the risk of infectious diseases in humans, including those caused by Hantavirus, lyssaviruses, and filoviruses.

CDC is also developing models to predict the spatial attributes of vulnerability to the direct effects of climate change—heat waves. Collaborations with university colleagues on four current projects use remote-sensing data to determine urban neighborhoods and populations most at risk for deaths during an extreme heat event. Research is also focusing on the knowledge, attitudes, and beliefs of the public on health issues related to climate change to effectively craft health education messages.

DEPARTMENT OF THE INTERIOR

Principal Areas of Focus

Climate change is one of the biggest challenges the world faces and is a top priority for the Department of the Interior and the U.S. Geological Survey (USGS). Climate change and its impacts on natural resources are a key concern for resource managers in the Department of the Interior and for many of Interior's external partners at State, Federal, and local levels. Work within the USGS Global Change activity supports the development of a framework for a comprehensive, national climate effects research and monitoring network and the adaptation of the scientific findings of the network to real life applications. Key components of the program office include:

- The DOI Climate Effects Network (DOI CEN)
- Global Change Research and Development
- Science Applications and Decision Support
- The National Climate Change and Wildlife Science Center
- National Carbon Sequestration Assessments (geologic and biologic).

The USGS Global Change Program supports the Department's goal to improve the understanding of national ecosystems and resources through integrated interdisciplinary assessments. Global Change-funded projects and activities support the goals described in the *2003 Strategic Plan.*

The USGS Global Change Program office is composed of two topical assessment centers and an integrated national observation and research network for determining and tracking the status and trends of whole systems subjected to a changing climate. The assessment centers are:

1. The National Climate Change and Wildlife Science Center
2. The National Carbon Sequestration Assessments

The topical centers will both contribute to and utilize the data collection, storage, and analysis capabilities

of the DOI CEN. The network will include three primary components of operation:

1. Collaborative Observation and Research (CORE) for Ecosystem, Land Use, and Socio-Economic Status and Trends
2. Global Change Research and Development
3. Science Applications and Decision Support

Program Highlights for FY 2010

DOI Climate Effects Network (DOI CEN)

In order to manage the impacts of climate change on resources, ecosystems, and human safety and well being, the Nation's citizens, policymakers, and managers of lands and trust resources need scientifically sound information about the effects of climate change on the Nation's land, water, and resources, and also on the effectiveness of the adaptation and mitigation actions we use to respond to climate change. The DOI CEN is designed to fulfill these needs, by building upon and leveraging existing resources within DOI, as well as the capabilities of many other Federal, State, and nongovernmental partners. The DOI CEN's four components are:

1. An inventory and evaluation of vulnerable monitoring infrastructure and existing capabilities for collecting and analyzing data;
2. Field-based observations that enhance our understanding of the effects of climate change on resources, ecosystems, and hazards from local to national scales;
3. Development of a system to manage, analyze, and disseminate information to the users of that information; and
4. Support for making decisions, including modeling to forecast future conditions, climate change related impacts, and the effectiveness of potential adaptation or mitigation actions.

These efforts dovetail with and leverage DOI statutory requirements to assess species vulnerabilities relative to the Endangered Species Act, to evaluate both geologic and biologic carbon sequestration potential on Federal lands, and carry out Interior trust responsibilities for managing those lands and the water, wildlife, and other resources upon them. Prototyping of regional- to local-scale, end-to-end knowledge base improvement and delivery is underway and yielding results in the Yukon River Basin, where climate change impacts are rapid and severe, and in selected other areas of the Nation at scales from local to national. The most urgently needed next phase of development is the design and implementation of a national strategy for early detection and tracking of environmental changes caused by climate change. This strategy could proceed incrementally, beginning with regions where climate change effects are most rapid and where the need for decision support is most pressing. Together, the DOI CEN components comprise a coherent plan to identify critical science needs for timely and effective land and resource management and to address them over short to long time periods and at local to national scales. Implementation of the DOI CEN will lead to better management of at-risk Interior assets and resources, more efficient and effective use of climate change information for managers, policymakers, and the public, and improved forecasting of the consequences of climate change for our environment, natural resources, and society.

USGS Global Change Research & Development

(R&D) includes environmental monitoring, research studies designed to understand the interactions between climate, Earth surface processes, and ecosystems on time scales ranging from years to millennia, and modeling of past, present, and future responses to potential changes in climate. By combining the expertise of hydrologists, geologists, biologists, geographers, and remote-sensing scientists, Global Change R&D conducts truly interdisciplinary research, modeling, and assessment of trends in environmental conditions in the following major focus areas:

- Climate history and past environmental change
- Impacts of climate change on landscapes, ecosystems, and organisms
- Hydrologic impacts of climate change
- Carbon cycle science
- Land use and land cover changes
- Decision support research and development.

The work conducted in the focus areas above provides data to improve the reliability of climate modeling efforts, to provide a rigorous science basis for support of adaptation and land and resource management decisionmaking, and to improve the Nation's ability to predict, adapt to, and mitigate climate-related impacts on landscapes, ecosystem goods and services, trust resources, and human communities. These research activities provide the scientific foundation for the DOI CEN, the National Climate Change and Wildlife Science Center (NCCWSC), and carbon sequestration efforts. Rigorous science is the basis for the development of an inte-

grated, systems-level understanding of changes in biogeochemical processes resulting from changes in climate, and helping to link these changes to the sustainability of ecosystems, wildlife, subsistence cultures, and societal infrastructure.

USGS Global Change R&D scientists produce key data sets and findings for use by citizens, policymakers, resource managers, and other scientists worldwide. Hundreds of peer-reviewed scientific papers and datasets are published each year. Recent major accomplishments include:

- A major paleoclimate data set now being used in the testing and validation of predictive climate models worldwide
- The first satellite atlas documenting the status of glaciers throughout Alaska
- A major study documenting and providing insight into rapid changes in Antarctic shelf ice and glaciers worldwide (slated for completion in FY 2010)
- Three major climate change assessments: Abrupt Climate Change, Thresholds in Ecosystems, and Arctic Paleoclimate (SAPs 1.2, 3.4, and 4.2, produced by USGS under the auspices of the USGCRP)
- Participation in a major climate change assessment on sea level rise in the mid-Atlantic (SAP 4.1, led by EPA in partnership with USGS and NOAA)
- Data on land use, sand movement, plant distributions, and climate change in support of Navajo Nation decisionmaking
- Integration of sea level rise vulnerability information into a pilot decision support framework
- Support of management decisions through studies of climate-related ecosystem change including the spread of invasive species
- Documentation of land cover change and trends from 1973 to 2000 (part of a national assessment slated for completion in FY 2010).

Science Applications and Decision Support

The USGS is in a unique position in the climate change research and applications community because of its ability to leverage and integrate research results across the Earth system science disciplines with *in situ* data, space-based and airborne observational data, high-end computing capabilities, data and information management systems, and decision support tool development. The Science Applications and Decision Support element of the USGS Global Change Program continues its efforts to develop decision support tools that enable resource managers and policymakers to cope with and adapt to a changing climate. Decision support will be developed through new partnerships, enhancement of existing collaborations, and in training the next generation of applications scientists. The USGS will shift Earth science research results to the operational missions of partnering agencies through the Science Applications and Decision Support element of the Global Change Program's DOI CEN.

The National Climate Change and Wildlife Science Center (NCCWSC)

The NCCWSC will address priority forecasting needs of natural resource managers and gather other critical information on which to base management and conservation actions. The NCCWSC will act as a conduit between science and management by linking physical climate models with ecological and biological responses at appropriate temporal and spatial scales to better inform management decisions and policy development. The forecasting products from climate models, regional ecological and biological response models, and vulnerability and risk assessments will enable fish, wildlife, and land managers to design suitable adaptive management approaches for their programs.

The focus of efforts continuing into FY 2010 includes:

- Establishment of the NCCWSC structure
- Initiation of national syntheses and forecasts with partners
- Coordination of regional stakeholder meetings to establish climate science partnerships
- Identification of decisionmaking processes and partners
- Initiation of regional forecasting pilot projects
- Development of ecological and biological response parameters at management scales
- Engagement with willing partners to apply NCCWSC forecasts and predictions, and to monitor and report results in adaptive management processes.

National Carbon Sequestration Assessments

Climate change poses new challenges to the traditional responsibility of the USGS for scientific assessment of the Nation's natural resources. One of the most important new resource assessment challenges is to determine the availability and vulnerability of carbon sequestration options, which have emerged as an important consideration

in many decisions affecting energy, land, water, and ecosystem resources. In 2007, the Energy Independence and Security Act (EISA; P.L. 110-140) mandated the DOI and USGS to conduct national assessments of potential sequestration in both ecosystems and subsurface rock formations. This responsibility requires comprehensive assessment methods that evaluate in a consistent manner the full range of biological and geological carbon sequestration options, including not only carbon storage by deliberate sequestration, but also conservation of existing carbon storage in soils and vegetation.

Comprehensive Assessment of Carbon Sequestration Resources

Assessment of the broad range of carbon sequestration options requires the unique breadth of USGS expertise in geology, biology, ecology, soil science, hydrology, geography, biogeochemistry, landscape analysis, modeling, and other specialties. USGS scientists work at the multiple spatial scales that are necessary to link national assessments to regional and local needs. USGS experience in resource assessment provides a background of practical cooperation with the wide range of partners and stakeholders who depend on independent, objective, and transparent scientific information for use in complex resource management decisions and policies.

Geologic Carbon Sequestration

Geologic storage of carbon dioxide (CO_2) in porous and permeable rocks involves injection of CO_2 into a subsurface rock unit and displacement of the fluid that initially occupied the pore space. Because the density of CO_2 is less than that of formation water, the injected CO_2 will be buoyant and will rise vertically until it is retained beneath a permeability barrier (seal). If the structure of the seal forms a trap with vertical and horizontal closure, CO_2 will accumulate in the same manner that buoyant fluids like crude oil and natural gas accumulate in nature. In addition to identification of adequate pore volume for CO_2 storage, a critical issue for evaluation of storage resources is the integrity and effectiveness of the seal that will retain the CO_2.

The USGS has recently completed a 12-month project to develop the methodology to assess the Nation's geologic resources for CO_2 storage in physical (oil and gas) traps and formations containing saline water (see <energy.er.usgs.gov/health_environment/co2_sequestration/>). After further review and public comment, this methodology will be finalized in anticipation of beginning the geologic sequestration resource assessment.

Biological Carbon Sequestration

CO_2 is removed from the atmosphere by both natural and deliberate processes that store carbon in vegetation, soils, and sediments. Deliberate carbon sequestration can be accomplished through forest and soil conservation practices that enhance the storage of carbon (such as restoring and establishing new forests, wetlands, and grasslands) or reduce CO_2 emissions (such as reducing agricultural tillage and suppressing wildfires). Carbon storage in ecosystems is susceptible to disturbances such as fire, disease, climate change, and changes in land use. Decisions about ecosystem carbon sequestration require careful consideration of risks, priorities, and tradeoffs among multiple resources.

Using long-established standards for resource assessment, USGS scientists are developing a methodology for assessment of carbon sequestration in ecosystems. In accordance with the EISA, this methodology will include procedures for assessment of ecosystem greenhouse gas fluxes and effects of management practices. National, regional, and local data sets, including remotely sensed information, will be used in a nationally consistent modeling framework to estimate potential future carbon sequestration and greenhouse gas fluxes.

DEPARTMENT OF STATE

Principal Areas of Focus

Through Department of State (DOS) annual funding, the United States is the world's leading financial contributor to the United Nations Framework Convention on Climate Change (UNFCCC) and to the Intergovernmental Panel on Climate Change (IPCC)—the principal international organization for the assessment of scientific, technical, and socioeconomic information relevant to the understanding of

climate change, its potential impacts, and options for adaptation and mitigation. Recent DOS contributions to these organizations provide substantial support for global climate observation and assessment activities in developing countries. DOS also works with other agencies in promoting international cooperation in a range of bilateral and multilateral climate change initiatives and partnerships.

PROGRAM HIGHLIGHTS FOR FY 2010

During FY 2010, DOS will continue to support the activities of the UNFCCC and the IPCC, and will advance and develop international climate and related energy partnerships.

DEPARTMENT OF TRANSPORTATION

PRINCIPAL AREAS OF FOCUS

The Department of Transportation (DOT) conducts research and uses existing science to improve decisionmaking tools to address climate change. DOT supports research that 1) examines the potential impacts of climate variability and change on transportation infrastructure and services, 2) examines increasing energy efficiency and reducing greenhouse gases, and 3) improves transportation greenhouse gas data and modeling. DOT has many programs that have either direct or indirect climate benefits, and is working to develop cross-modal strategies to reduce greenhouse gas emissions.

DOT's Climate Change Center is the Department's focal point for information and technical expertise on climate change. The Center coordinates research, policies, and actions related to transportation and climate change with DOT's component organizations. Supporting DOT's core goals of safety, mobility, environmental stewardship, and security, the Center promotes comprehensive approaches to reduce greenhouse gases, to prepare for the potential impacts of climate change, and to develop necessary adaptations to transportation operations and infrastructure. The Center supports the program goals through these objectives. Specifically, the Center aims to inform Goal 4 by identifying and providing scientific inputs for evaluating adaptation options and Goal 5 by supporting adaptive management and planning for physical infrastructure sensitive to climate variability and change.

In addition to participating in the Center, the Federal Aviation Administration (FAA) has programs to assess and identify potential measures to reduce fuel consumption and greenhouse gas emissions. FAA conducts research to support Goal 2, leveraging research with other U.S. Government agencies to reduce uncertainties surrounding aviation emissions and their effect on climate change. For example, FAA research through the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence addresses the impact of aircraft contrails on climate change. FAA also participates heavily in the work program of the International Civil Aviation Organization's Committee on Aviation Environmental Protection, and provides technical expertise and data to the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC).

PROGRAM HIGHLIGHTS FOR FY 2010

DOT's Climate Change Center is undertaking several research projects that support Goals 4 and 5:

- Refining a tool to allow comparative analysis of emissions from different modes of transportation, including aviation, automobile, marine, and diesel transportation
- Conducting an emissions analysis of freight transport, comparing land-side and water-side short-sea routes to develop and demonstrate a decision modeling tool
- Determining the potential effects of sea level rise on national transportation infrastructure
- Preparing a study of the impact of the Nation's transportation system on climate change and solutions to mitigate climate change by reducing greenhouse gas emissions from the transportation sector
- Conducting a pilot project to record best practices for metropolitan planning organizations to incorporate climate change into transportation planning.

The Center sponsored Synthesis and Assessment Product 4.7, *Impacts of Climate Variability and Change on Transportation Systems and Infrastructure–Gulf Coast Study*. This project—initiated under the President's Climate Change Research Initiative—was a joint research effort with USGS. A Federal Advisory Committee was formed in 2006, and Phase I was completed in 2007. Phase I provided an integrated overview of infrastructure sensitivities in the region. The final document was released in March 2008. Work will begin soon on Phase II of the study, which will better inform planners and decisionmakers and develop risk assessment tools for analysis.

The Center also developed the Transportation and Climate Change Clearinghouse (<climate.dot.gov>). The Clearinghouse includes information on greenhouse gas inventories, analytic methods and tools, emissions reduction strategies, potential impacts of climate change on transport infrastructure, and approaches for integrating climate change considerations into transportation decisionmaking.

FAA continues to develop a comprehensive suite of software tools to allow for the thorough assessment of the environmental effects and impacts of aviation.[1] One element of the tools suite is the Aviation Environmental Design Tool (AEDT), which incorporates the legacy System for assessing Aviation's Global Emissions (SAGE) tool. AEDT/SAGE takes as input detailed fleet descriptions and flight schedules, and produces estimates of noise and emissions inventories and fuel consumption at global, regional, and local levels. The tool can also estimate future output based upon forecasts, including potential technology advances or operational improvements, as well as the influence of potential market-based measures to reduce fuel consumption and greenhouse gas emissions. Data from AEDT/SAGE are used to calculate the FAA's Flight Plan aviation fuel efficiency goal.

[1] See <www.faa.gov/about/office_org/headquarters_offices/aep/models>

AGENCY FOR INTERNATIONAL DEVELOPMENT

Principal Areas of Focus

The U.S. Agency for International Development (USAID) supports a number of programs that enable decisionmakers to apply high-quality climate information to decisionmaking.

The Famine Early Warning System Network (FEWS NET) continues to provide short- and long-term climate forecasts in the developing world that help to enhance the adaptive capacity of developing countries coping with climate variability and change. FEWS NET produces a number of regular reports that combine meteorological data with ground-based livelihoods information to provide information on food security within a number of developing countries. These reports are publicly available and include *Food Security Updates*, a monthly report with comprehensive coverage of current and projected food security conditions and their implications; and *Alerts*, one-page statements issued when a crisis is emerging or deteriorating or when early action is recommended. This information will better enable development agencies and regional and local institutions to direct appropriate resources and support toward strengthening the adaptive capacity of affected groups and the food production systems upon which they depend.

USAID recently released *Adapting to Coastal Climate Change: A Guidebook for Development Planners* as a follow-up to the 2007 Adaptation Guidance Manual. This Guidebook presents a framework and approach for assessing coastal vulnerabilities and specific measures for reducing vulnerability. It is designed to address the needs of decisionmakers and coastal managers.

Program Highlights for FY 2010

USAID will expand upon the recently initiated adaptation guidance and training, focusing on several climate-reliant development sectors. The first sector

to be considered is water guidance, focusing on changes in both water availability and quality and addressing issues associated with agriculture, glacier loss, and urban areas. The guidance will be developed with and informed by several pilot studies.

ENVIRONMENTAL PROTECTION AGENCY

Principal Areas of Focus

The core purpose of the Global Change Research Program in the U.S. Environmental Protection Agency (EPA) Office of Research and Development is to provide scientific information to stakeholders and policymakers to support them as they decide whether and how to respond to the risks and opportunities presented by global change. The program is stakeholder-oriented, with primary emphasis on assessing the potential consequences of global change (particularly climate variability and change) on air quality, water quality, aquatic ecosystems, and human health in the United States. The program's focus on these four areas is driven by EPA's mission and statutory and programmatic requirements. EPA uses the results of these studies to investigate adaptation options to improve society's ability to effectively respond to the risks and opportunities presented by global change, and to develop decision support tools for resource managers coping with a changing climate. EPA has also invested in decision support tools to help decisionmakers evaluate alternative strategies for reducing greenhouse gas emissions and the environmental implications of those strategies.

The program uses a place-based approach because the impacts of global change and their solutions are often unique to a location (e.g., a watershed). Partnerships are established with locally based decisionmakers to ensure that the program is responsive to their unique scientific information needs and the socioeconomic realities at their locales.

EPA's work is consistent with and closely coordinated with the *2003 Strategic Plan*. Planning and implementation of EPA's program is integrated with other participating Federal departments and agencies to reduce overlaps, identify and fill programmatic gaps, and add value to products and deliverables produced under the USGCRP's auspices. EPA coordinates with other USGCRP agencies to develop and provide timely, useful, and scientifically sound information to decisionmakers. EPA is committed to support of USGCRP's research and assessment activities. This commitment includes assessments uniquely focused on EPA's mission and statutory requirements (e.g., assessments of the impacts of global change on air and water quality) and support for the USGCRP to produce periodic assessments of the potential impacts of climate change for Congress. Also, as called for by the National Research Council in 2001, EPA supports and fosters projects that link the producers and users of knowledge in a dialog that builds a mutual understanding of what is needed, what can credibly be said, and how it can be said in a way that maintains scientific credibility.

EPA's program has two major areas of emphasis: air quality and water quality. Within these two areas, the program evaluates the human health consequences and the consequences for ecosystems of the changes in air quality and water quality likely to result from global change.

Air Quality

The primary focus of EPA's work in air quality is to assess how climate change will affect air quality and how the resultant change in air quality is likely to affect human health. Studies are underway and publications have been released that provide the approaches, methods, and models to quantitatively evaluate the effects of global change on air quality. Since health outcomes are affected by a variety of social, economic, political, environmental, and technological factors, investigating the health impacts of global change and air quality is a complex challenge. As a result, health studies in EPA's Global Change Research Program go beyond basic epidemiological research to develop integrated health evaluation frameworks that consider the effects of multiple stresses, their interactions, and human adaptive responses. Along with health sector studies conducted in conjunction with other USGCRP agencies, there are research activities focused on the possible consequences of global change on weather-related morbidity and vector- and water-borne diseases. In addition, EPA's program in air quality will identify

technology advancements and adaptive responses and quantify their effects on air quality.

Water Quality

EPA's mission is to protect human health and safeguard the natural environment. EPA provides environmental protection that contributes to making communities and ecosystems diverse, sustainable, and economically productive. Consistent with this goal, EPA's Global Change Research Program is assessing the impacts of global change on water quality and aquatic ecosystems in the United States.

Water quality is affected by changes in runoff following changes in precipitation and evapotranspiration and changes in land use. The program is investigating the impacts of global change (climate and land use change) on water quality using a watershed approach. A major focus is on studying the sensitivity to climate change of goals articulated in the Clean Water Act and the Safe Drinking Water Act, and the opportunities available within the provisions of these Acts to address anticipated impacts.

The program has research activities that evaluate the effects of global change on aquatic ecosystems (which may include lakes, rivers, and streams; wetlands; and estuaries and coastal ecosystems), invasive non-indigenous species, and ecosystem services. EPA's investigations of the effects of global change on aquatic ecosystems uses as input the research being done by other USGCRP agencies on marine and terrestrial ecosystems. Therefore, EPA's ability to successfully complete its assessments depends crucially upon the ability of other USGCRP agencies to complete their related research activities.

Extramural Research

Intramural and extramural research contributes to all of EPA's investigations. In an attempt to capitalize on expertise in the academic community, a portion of the program's resources is dedicated to extramural research grants administered through the STAR (Science to Achieve Results) program. The STAR program focuses on science to support investigations of the consequences of global change for air quality, ecosystems, and human health in the United States. EPA will continue to coordinate closely with other USGCRP agencies to identify the specific topics that should be emphasized within the STAR program.

Program Evaluation

The EPA Global Change Research Program is evaluated through extensive review by EPA's independent Board of Scientific Counselors (BOSC). A review in 2006 by the BOSC concluded that the program has conducted the "right work" and done it "well." The program "has provided substantial benefits to the Nation" and "is on course to make significant further contributions to societal outcomes by informing and facilitating decisions by the public and private sector actors who must consider the prospects of global change."

Program Highlights for FY 2010

EPA will continue to make significant contributions to the ongoing research activities of the USGCRP, and provide timely and useful information to resource managers coping with a changing climate. EPA-sponsored investigations will be conducted through partnerships that actively engage researchers from the academic community, decisionmakers, resource managers, and other affected stakeholders. Highlights of specific activities to be completed by or initiated in FY 2010 include:

- Release of a final report on the impacts of climate change on regional U.S. air quality with a focus on ground-level ozone
- Completion of the nine-region MARKAL model of the United States. The MARKAL model is an energy-technology-environmental systems model that predicts future emissions
- Final report on the potential impacts of climate change on combined sewer overflow mitigation in the Great Lakes and New England regions
- Report on the development of land use scenarios consistent with climate change emissions storylines
- Final report and user manual for the BASINS Climate Assessment Tool that enables water resource managers to assess the influence of climate change on water quality and quantity,
- Release an online Climate Assessment Tool (WEPPCAT) that provides resource managers with the ability to assess and manage impacts of climate change on sediment loadings to streams
- In conjunction with NOAA, the completion of a study by the National Research Council on strategies and methods for climate-related decision support

Related Research

In addition to focused USGCRP activities, EPA conducts research that contributes to the characterization and understanding of risks to ecosystems and to human health. The ecosystems-

based research is designed to understand and predict the impacts on ecological goods and services from chemical (e.g., nutrients) and non-chemical stressors (e.g., invasive species, genetically altered organisms). The research in human health is oriented toward assessing the cumulative health risks to humans (e.g., cancer, reproductive, cardiovascular)—including high-risk subpopulations (e.g., children)—from chemical stressors emanating from multiple sources. Both of these major research areas will be affected by and are inextricably interrelated with climate change.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Principal Areas of Focus

The National Aeronautics and Space Administration (NASA) conducts a program of breakthrough research to advance fundamental knowledge on the most important scientific questions about the global and regional integrated Earth system. NASA's program encompasses most themes of the *2003 Strategic Plan* for the USGCRP.

NASA continues to enhance the ability of the international scientific community to advance global integrated Earth system science using space-based observations. The research encompasses the global atmosphere; the global oceans including sea ice; land surfaces including snow and ice; ecosystems; and interactions between the atmosphere, oceans, land, and ecosystems, including humans. NASA's goal is to understand the changing climate, its interaction with life, and how human activities affect the environment. In association with national and international agencies, NASA applies this understanding for the well-being of society.

NASA presently has 15 on-orbit satellite missions: ACRIMSAT, Aqua, Aura, CALIPSO, CloudSat, EO, GRACE, ICESat, Jason, Landsat-7, OSTM, QuikSCAT, SORCE, Terra, and TRMM. The acronyms for these missions are defined in Appendix C, and Table 1 lists the primary USGCRP themes of the operating missions. On 24 February 2009, NASA's Orbiting Carbon Observatory (OCO) satellite did not reach orbit altitude when the launch vehicle malfunctioned. NASA has five missions in development for launch between 2010 and 2014. The National Research Council (NRC) Decadal Survey mission priorities are the principal determinant of the priority of NASA's Earth Science satellite missions beyond those currently in development. The NRC Decadal Survey satellite mission Soil Moisture Active-Passive (SMAP) is in Phase A formulation and concept development study and the Ice, Cloud, and Land Elevation Satellite (ICESat II) mission is expected to begin Phase A in FY 2010

NASA aircraft- and surface-based instruments are used to calibrate and enhance interpretation of high-accuracy, climate-quality, stable satellite measurements. NASA supports state-of-the-art computing capability and capacity for extensive global integrated Earth system modeling. NASA, in recording approximately four terabytes of data every day, maintains the world's largest scientific data and information system for collecting, processing, archiving, and distributing Earth system data to worldwide users.

Program Highlights for FY 2010

NASA will make significant progress in FY 2010 in all themes of the *2003 Strategic Plan*.

Atmospheric Composition

Atmospheric composition determines air quality and affects weather, climate, and critical constituents such as ozone and carbon dioxide. Solar radiation affects atmospheric chemistry and is a critical factor in atmospheric composition. NASA's research for furthering our understanding of atmospheric composition will provide an improved prognostic capability for issues such as the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality. NASA expects to provide the necessary observations and evaluation tools to assess the effects of climate change on ozone recovery and future atmospheric composition, improved climate forecasts based on understanding the forcings of environmental change, and air quality forecasts that take into account the interactions between regional air quality and global

climate change. NASA's integrated observational and modeling strategy is furthered through studies of atmospheric processes using unique airborne platform sensor combinations to investigate, for example, the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and its destruction in the stratosphere.

In FY 2010, new research will focus on factors influencing tropospheric air quality including the emission, transport, and oxidation of hydrocarbons, carbon monoxide, and nitrogen oxides, aerosol processes, and exchange between the troposphere and stratosphere. Research topics include the effects of climate change on air quality, the climate impact of chemically active trace gases and aerosols, and the representation and attribution of changes in air quality over the past 20 years.

The Glory mission will be launched in FY 2010 to improve NASA's research on aerosol forcing of climate change. The major science objective of the Glory mission is the determination of the global distribution, microphysical properties, and chemical composition of natural and anthropogenic aerosols to quantify the aerosol direct and indirect effects on climate. Measurements from the Glory Aerosol Polarimetry Sensor (APS) instrument will be essential to predicting future climate change. Glory will also carry a Total Irradiance Monitor (TIM) to continue the 30-year measurement record of total solar irradiance and thus provide a key data set needed to determine the Sun's direct and indirect effect on climate.

Glory will become the sixth satellite in the Afternoon (A)-Train, with which an unprecedented quantity of atmospheric chemistry and composition measurements will be recorded within seven minutes along the same ground track. In FY 2010, NASA will research methodologies to advance the air quality management community's use and application of A-Train observations, particularly issues associated with the implementation of air quality standards, policy, and regulations for environmental, economic, and human welfare.

In May and June 2010, the Mid-latitude Airborne Cirrus Properties Experiment (MACPEX) will focus on cirrus cloud-chemistry interactions during the summer over Oklahoma. Measurements from NASA's WB-57 aircraft

Correlation of NASA Operating Satellite Missions with USGCRP Scientific Themes

Satellite	Launch Date	USGCRP Science Focus Areas
ACRIMSAT	December 1999	Climate variability and change
Aqua	May 2002	Atmospheric composition; carbon cycle; climate variability and change; ecosystems; water cycle
Aura	July 2004	Atmospheric composition
CALIPSO	April 2006	Atmospheric composition; water cycle
Cloudsat	April 2006	Water cycle; climate variability and change
EO	November 2000	Carbon cycle; ecosystems
GRACE	March 2002	Climate variability and change; water cycle
ICESat	January 2003	Climate variability and change; water cycle
Jason	December 2001	Climate variability and change; water cycle
Landsat-7	April 1999	Carbon cycle; ecosystems
OSTM	June 2008	Climate variability and change; water cycle
QuikSCAT	June 1999	Climate variability and change
SORCE	January 2003	Atmospheric composition; climate variability and change
Terra	December 1999	Atmospheric composition; carbon cycle; climate variability and change; ecosystems; water cycle
TRMM	November 1997	Climate variability and change; water cycle

should provide the cirrus microphysical information needed for improvement and evaluation of remote-sensing retrievals and for climate model cloud parameterizations. MACPEX will provide measurements to examine the relationship between small (diameter <50 microns) crystals in cirrus and aerosol loading and composition.

Climate Variability and Change

A unique NASA contribution to climate science is the frequent near-global coverage of observations from space of many properties of the integrated Earth system. NASA provides observations of critical elements of the climate system, including ice sheets, sea ice, sea level, clouds, snow cover, solar radiation, and humidity.

Over the past five years, ICESat has measured ice sheet elevation changes for determination of the mass balance of the Antarctic and Greenland Ice Sheets to improve estimates of their contributions to global sea level rise. During early FY 2010, ICESat's final laser instrument is projected to have limited power. To mitigate the data gap between the on-orbit ICESat mission and the NRC Decadal Survey ICESat II mission, NASA will conduct IceBridge missions beginning in FY 2009 with aircraft to measure the elevations of the ice sheets in Antarctica and Greenland, as well as to determine the thickness of sea ice in the Arctic and Southern Oceans. NASA will continue ICESat research themes on ice sheet thickness, sea ice freeboard and inferred thickness, and properties of Antarctic subglacial lakes.

The launch of OSTM in June 2008 extends the high-accuracy, well-calibrated global sea level measurements initiated in 1992. These observations continue to show a faster global sea level rise compared to many climate model results. In FY 2010, NASA will support new research investigations on ocean circulation, both global and regional, using OSTM and other altimetry data in conjunction with QuikSCAT ocean vector wind measurements. NASA is also playing a central role in providing the next-generation data products for sea surface temperature with new research investigations beginning in FY 2010.

In anticipation of the launch of NASA's Aquarius sea surface salinity instrument on an Argentine satellite in FY 2010, NASA has selected a new science team to explore the role of salinity in ocean circulation and the global water cycle. NASA continues to contribute significantly to the U.S. Ocean Action Plan Near-term Opportunity to assess the potential for rapid climate change associated with the Atlantic meridional overturning circulation.

In FY 2010, NASA will develop climate model analyses for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), as described below in Modeling Strategy.

Global Water Cycle

The water cycle involves water in all three of its phases, including clouds and precipitation; ocean-atmosphere, cryosphere-atmosphere, and land-atmosphere interactions; mountain snow; and groundwater.

NASA is accurately assessing the key water reservoirs and fluxes, including their spatial and temporal variability, through integration of satellite and *in situ* observations and models. The cycling of water through the global integrated Earth system has obvious and significant implications for the health and prosperity of society.

In FY 2010, NASA investigations will focus on water cycle changes that may occur as atmospheric water storage becomes larger with increased global warming. Projects initiated in FY 2009 will fuse together information from multiple NASA satellites to improve estimates of the evaporation of water from land and ocean and will investigate water cycle dynamics in extreme events, such as floods and droughts. These activities will refine methods of evaluating the ability of climate change models to simulate global water cycle structure and variability.

NASA is planning the Genesis and Rapid Intensification Processes (GRIP) airborne campaign for summer 2010 to better understand how tropical storms form and develop into major hurricanes. NASA plans to use the DC-8 aircraft and the Global Hawk Unmanned Airborne System. GRIP deployment is planned in Miami, Florida for the DC-8, and Edwards, California (or Wallops Island, Virginia) for the Global Hawk. The Global Hawk will fly in the upper troposphere and stratosphere, and, with 30-hour flight duration, can easily reach all regions of the Atlantic, Caribbean, and Gulf of Mexico.

In FY 2010, NASA will continue the concept and technology formulation phase of the Decadal Survey-recommended Soil Moisture Active-Passive (SMAP) satellite mission to measure soil moisture and determine the freeze/thaw state of the soil when

launched in 2013 or 2014. SMAP data will contribute to determining water fluxes between the atmosphere and land surface; extending the capabilities of medium-range weather forecast models and seasonal climate models; and determining whether the soil in Northern Hemisphere high latitudes is a carbon sink or source.

Land Use and Land Cover Change

NASA develops the scientific understanding and models necessary to simulate land cover and land use changes, including evaluating consequences for the carbon and water cycles and for human interaction with the environment. This research will develop a scientific foundation for sustainability, vulnerability, and resilience of land systems and their use.

In FY 2010, NASA and the USGS will continue collecting observations from Landsat-5 and Landsat-7 to contribute to a new international global land survey (GLS) data set produced from images recorded from 2009 to 2011. Land cover changes over 35 years will be analyzed using comparative analyses of the new GLS data with previous GLS data sets constructed for 1975, 1990, 2000, and 2005. In FY 2010, NASA will continue to support scientific investigations on land use and land cover change interactions with climate and ecosystems.

Global Carbon Cycle

NASA research on the global carbon cycle addresses the distribution and cycling of carbon among the terrestrial, oceanic, and atmospheric reservoirs.

In FY 2010, NASA will continue developing continental-scale satellite data products and conducting synthesis research for the North American Carbon Program (NACP). Regional modeling and data assimilation studies to simulate the recent historical period will be analyzed to assess changes in carbon source and sink strength.

In FY 2010, new investigations will be conducted on carbon dynamics in Northern Hemisphere high latitudes. NASA will begin a program of ship and satellite measurements in the Arctic Ocean to study the impact of climate change, both natural and anthropogenic, on the biogeochemistry of the Chukchi and Beaufort Seas. The program will include focused, multi-scale data assimilation experiments and model studies. Terrestrial ecosystem studies will emphasize quantifying regional carbon dioxide and methane fluxes and the processes controlling them, and analyzing the impacts of potential carbon cycle changes, including abrupt changes. Modeling will address the response of carbon currently stored frozen in peatlands or permafrost soils and how fire activity and severity affect carbon storage in northern ecosystems.

Ecosystems

NASA improves understanding of the structure and function of global marine and terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in cycling biogeochemical elements. In FY 2010, research will focus on ecological impacts of, adaptation to, and vulnerability to global climate change and on studies to prepare for ecological applications of data from Decadal Survey missions.

In FY 2010, NASA ecological forecasting studies will focus on the distribution and abundance of ecosystems and species. Research investigations will integrate satellite and *in situ* measurements with ecological models to forecast changes in aquatic and terrestrial ecosystems and species of importance to resource managers.

NASA, in partnership with the National Oceanographic Partnership Program (NOPP), will lead the U.S. Ocean Action Plan Near-term Opportunity to develop sensors for measurement of biological, bio-optical, optical, and chemical properties of the ocean. Studies will be initiated to advance the scientific basis for new satellite missions that will measure ecosystem three-dimensional structure and ecosystem functional indicators.

Modeling Strategy

Quantitative understanding of Earth system processes and feedbacks is codified in climate models. The Earth System Modeling Framework—which was initiated in 2002 by NASA and now is an interagency activity—enables shared infrastructure and interoperability of model components and interfaces.

During FY 2010, NASA will continue developing the Goddard Space Flight Center (GSFC) Earth Observing System (GEOS) Earth System Model by incorporating chemistry-physics coupling throughout the atmosphere, and integrating atmosphere, ocean, biogeochemistry, and land modules. A novel gridding approach will enable higher spatial resolution with reduced filtering requirements. Future plans include incorporating non-hydrostatic dynamics allowing evaluation across

a broad spectrum of temporal and spatial scales ranging from weather to climate.

In FY 2010, NASA will develop climate model analyses for the IPCC AR5. NASA's Goddard Institute for Space Studies (GISS) Model E will be improved for the effort, with doubled geographic resolution and upgraded representations of atmospheric physical processes. NASA will collaborate with the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and Earth System Grid (ESG) to facilitate the exchange and intercomparison of model data.

Decision Support Resources Development

NASA develops and demonstrates practical applications of its research satellite observations and model results for use by decisionmakers. NASA works directly with decisionmakers throughout the development of applications. Examples include improved public health tracking systems for deadly diseases with the Centers for Disease Control; advances in prediction of weather conditions for airplane pilots through the National Weather Service and the Federal Aviation Administration; improved tracking of air pollutants with EPA for decisionmaking on biomass burning and industrial practices; improving the USDA's Global Economic Forecasting; and providing tools for better disaster management by State and local first responders.

In FY 2010, NASA will focus its application activities across many sectors likely to be affected by climate change, such as agriculture, public health, and water resources, emphasizing integration of regional impacts and adaptation into decisionmaking. In 2010, NASA will sponsor two types of competitively selected projects across this range of applications areas: Decision Support through Earth Science Research Results and Earth Science Applications Feasibility Studies.

Observing and Monitoring the Climate System

Global measurements to understand the physical, biological, chemical, and ecosystem processes responsible for changes in the Earth system at all relevant spatial and temporal scales are critical to understand past and present climate changes and predict future climate change. NASA continues to provide sustained, high-accuracy, well-calibrated, stable global observations with high spatial and temporal resolutions for a number of environmental parameters.

In FY 2010, NASA will launch two new satellite missions. The Glory satellite mission will measure microphysical properties of aerosols to determine how aerosols contribute to net cooling or warming. Glory will join the A-Train to improve understanding of the interactions between aerosols and clouds and other phenomena. Glory will also extend the time series of total solar irradiance at the top of the atmosphere. Begun in 1979, the time series is one of the longest global data sets recorded by a series of satellites. The NASA Aquarius sea surface salinity instrument on an Argentine satellite will measure global sea surface salinity with a 150-km spatial resolution on a 30-day time scale with an error of less than 0.6%. The Aquarius data coverage will extend to about 88°N where summer sea ice no longer exists.

Data Management and Information

NASA has led development of data management and information systems to create seamless, platform-independent, timely, open access to integrated data products and information to address global integrated Earth system science.

In FY 2010, NASA will continue research on efficient methods to connect NASA data with other relevant data sources and systems, and on integration of multiple data, metadata, and advanced services. NASA will develop techniques to link together data from multiple satellites, create Earth system data records, and improve the access, use, and interoperability of satellite data.

NATIONAL SCIENCE FOUNDATION

PRINCIPAL AREAS OF FOCUS

National Science Foundation (NSF) programs address global change issues through investments that advance frontiers of knowledge and provide state-of-the-art instrumentation and facilities while also cultivating a diverse highly trained workforce and developing resources for public education. In

particular, NSF global change research programs support research and related activities to advance the fundamental understanding of physical, chemical, biological, and human systems and the interactions among them. The programs encourage interdisciplinary activities and focus particularly on Earth system processes and the consequences of change for organisms and ecosystems and the essential services they provide to society. NSF programs facilitate data acquisition and information management activities necessary for fundamental research on global change, and promote the enhancement of models designed to improve understanding of Earth system processes and feedbacks that link ecosystems to global climate systems, and develop advanced analytic methods to facilitate basic research. NSF also supports fundamental research on the processes used by organizations to identify and evaluate policies for mitigation, adaptation, and other responses to the challenge of varying environmental conditions. Through its investment, NSF contributes to the overall goals identified in the *2003 Strategic Plan*.

Program Highlights for FY 2010

Atmospheric Composition

NSF programs in tropospheric and stratospheric chemistry will continue to address the composition of the atmosphere and its relation to climate variability and change. Studies of the transformation and transport of gaseous constituents and aerosols provide insights into the radiative and cloud nucleating properties of the atmosphere. Studies of the global distributions of greenhouse gases and aerosols will provide input for future scenarios of radiative forcing.

Climate Variability and Change

NSF programs maintain a strong emphasis on climate variability and change across temporal and spatial scales through a combination of observational campaigns and numerous analytical and modeling activities. These activities will help to improve parameterizations of unresolved dynamics and address biases in global climate models. Ocean science efforts will focus on changes in the Atlantic meridional ocean circulation, its interactions with the atmosphere, and the potential for abrupt change. Studies of decadal variability and changes in the statistics of extreme weather events will be an area of emphasis. The Community Climate System Model (CCSM) continues to incorporate additional complexity with small-scale ocean processes, interactive chemistry, and biogeochemical cycles. Coupled climate model studies on decadal predictability at regional scales will be initiated and will include exploratory research on initialized climate modeling. Studies of paleoclimatology will continue to be supported as a means to provide baseline data on natural climate variability from the past and from key climatic regions and to enable reconstructions and evaluations of past environmental change as inputs for model validations.

Global Water Cycle

NSF supports a broad-based effort to understand all aspects of the global water cycle with continued emphasis on interdisciplinary research. Relevant programs will continue to explore ways to optimally and effectively utilize the wide range of hydrological data types, which include continuous and discrete temporal and spatial information from a variety of platforms. A community-initiated Hydrologic Information System (HIS), which provides improved data access as well as analysis tools, continues to expand, serving both research and operational communities. Process study data will be used to refine models through scaling and parameterizations of sub-grid processes, particularly the fluxes of water through the Earth system. High-resolution cloud system models are being used to address persistent problems in representing moist convection and cloud processes in climate models. NSF will expand capabilities at its Critical Zone Observatories that are used to study the coupling of Earth surface processes as mediated by the flux of fresh water. The Sustainability of Semi-arid Hydrology and Riparian Areas (SAHRA) Science and Technology Center, working with regional stakeholders, is translating research advances into useful products and addressing uncertainty.

Land Use and Land Cover Change

Several NSF programs continue to address key aspects of land use and land cover change through studies of ecological rates of change and related aspects of biodiversity; Arctic systems; temporal variability; water and energy influences on vegetative systems; fire-land cover interactions; and diverse human influences on land use. They also support research that examines how biophysical processes associated with changes in land use and land cover feed back to the climate system.

Global Carbon Cycle

NSF supports a wide variety of carbon cycle research activities, from critical and long-running oceanic time series stations and the Keeling carbon dioxide

measurements to plot-based process measurements and planning and data management. Investigations examine a range of topics in terrestrial and marine ecosystems and their relations to the carbon cycle. Research in terrestrial settings will explore, for example, carbon storage, controls on carbon exchange between ecosystems and the atmosphere, delivery of carbon by rivers, carbon fluxes from wetlands and high-latitude soils, the role of microbial processes and aspects of biodiversity in fluxes between carbon pools, and carbon export from mountains and submarine groundwater discharge. In marine systems, studies on the role of ocean acidification, including the coupling of the nitrogen and carbon cycles, will be addressed. Carbon cycle studies will integrate observational data into models to provide insights for understanding key aspects of the global carbon cycle.

Ecosystems

Several NSF programs support investigations of the effects of climate change on terrestrial and marine ecosystems and the consequences of those changes for climate through observational, experimental, modeling, and laboratory studies. A major source of information and knowledge of climate-ecosystem interactions in terrestrial, freshwater, and marine systems comes through the Long-Term Ecological Research (LTER) network and related observing sites in the United States and adjacent oceans, as well as associated modeling efforts. The Global Ocean Ecosystem Dynamics program will continue to study the impact of global ocean changes on marine ecosystems through specific synthesis activities focused on the North Atlantic, North Pacific, and Southern Ocean systems. NSF also supports studies of the production and consumption of greenhouse gases and aerosols by terrestrial and freshwater biota, the role of ocean biota in the uptake and cycling of greenhouse gases in the ocean, and the impacts of ocean acidification.

Human Contributions and Responses

NSF supports basic research on the processes through which people (individually, in groups, or through organizations) interact with natural environmental systems, including research on vulnerability and resilience and their relation to adaptation strategies. Programs support projects that focus on decisionmaking under uncertainty associated with climate change. These projects are expected to produce new knowledge and tools that should facilitate improved decisionmaking by various stakeholder groups trying to deal with uncertainties associated with future climate variability and change. In addition, climate studies will be a major theme in NSF's cross-directorate program, Dynamics of Coupled Natural and Human Systems, which examines the complex interactions among these systems.

International Research and Cooperation

The International Polar Year 2007-2008 (IPY) ran from March 2007 through March 2009, with NSF as the designated lead Federal agency. With the successful completion of the observational phase, NSF IPY activities will focus on analyses of newly acquired data sets aimed at improving understanding of climate change in both polar regions and on linkages between polar and global systems. Stratospheric and tropospheric chemistry over Antarctica and the Southern Ocean carbon cycle remain important foci. In addition, NSF, in cooperation with NASA and international partners, will continue a major longer-term study to elucidate how sea level is changing in concert with changes in the stability of the Greenland and Antarctic Ice Sheets.

Related Research and Education Efforts

NSF will continue to support "contributing" research on broader topics that are closely related to global and climate change, and add substantively to the specific programs supporting USGCRP objectives. Enhancement to computing infrastructure will enable more effective utilization of the research information. NSF also supports projects that integrate research with education on global and climate change. Students explore climate-related issues by evaluating multimedia data at various spatial and temporal resolutions, reviewing scientific evidence, and considering social concerns that contribute to global and climate change debates. In collaboration with other agencies, NSF is working with the geosciences education community to develop a framework for Earth System Science Literacy.

SMITHSONIAN INSTITUTION

National Air and Space Museum (NASM)
National Museum of Natural History (NMNH)
National Zoological Park (NZP)
Smithsonian Astrophysical Observatory (SAO)
Smithsonian Environmental Research Center (SERC)
Smithsonian Tropical Research Institute (STRI)

PRINCIPAL AREAS OF FOCUS

Within the Smithsonian Institution, global change research is conducted at the Smithsonian Astrophysical Observatory, the National Air and Space Museum, the Smithsonian Environmental Research Center, the National Museum of Natural History, the Smithsonian Tropical Research Institute, and the National Zoological Park. Research is organized around themes of atmospheric processes, ecosystem dynamics, observing natural and anthropogenic environmental change on daily to decadal time scales, and defining longer-term climate proxies present in the historical artifacts and records of the museums as well as in the geologic record at field sites. The Smithsonian Institution program strives to improve knowledge of the natural processes involved in global climate change, to provide a long-term repository of climate-relevant research materials for present and future studies, and to bring this knowledge to various audiences, ranging from scholarly to the lay public. The unique contribution of the Smithsonian Institution is a long-term perspective—for example, undertaking investigations that may require extended study before producing useful results and conducting observations on sufficiently long (e.g., decadal) time scales to resolve human-caused modification of natural variability.

PROGRAM HIGHLIGHTS FOR FY 2010

Atmospheric Composition
At SERC, measurements will be made of spectral ultraviolet-B (UV-B) radiation in Maryland (>30-year record), Florida, Arizona, and other sites in the United States. These data will be electronically disseminated to meet the needs for assessing the biological and chemical impact of varying ultraviolet radiation exposures.

Climate Variability and Change
Research at NASM will emphasize the use of remote-sensing data to improve theories of drought, sand mobility, soil stability, and climate change in the Mojave Desert and Simpson Desert, Australia. Studies at NMNH and STRI will focus on the paleoecology of climate change.

Terrestrial and Marine Ecosystems
Several Smithsonian programs will examine biological responses to global change. At SERC, research will be conducted on the responses of global ecosystems to increasing carbon dioxide concentrations (also a contribution to the Global Carbon Cycle program). This SERC program will also focus on invasive species and solar UV-B radiation. Biodiversity education and research will be performed at STRI, NMNH, and NZP. Tropical biodiversity research programs monitor global change effects through repeated sampling of flora and fauna in tropical and temperate forests, and identifying the physical and biological processes of growth and decline of species. In FY 2010, this effort will be expanded through the Smithsonian Institution Global Earth Observatories initiative (SIGEO). This initiative will increase the Federal sponsorship, and thus long-term continuity, of forest population censuses in 34 plots in 22 countries as needed to document the effects of climate change and disseminate those results widely. It will also augment censuses with complementary remote sensing and modeling of carbon fluxes, and attain a more global perspective of forests by extending monitoring to temperate forest plots at SERC and NZP's Conservation and Research Center. Work at the latter two sites will be coordinated with NSF's proposed National Ecological Observatory Network (NEON), should it be built. Other studies on ecosystem response to increasing habitat fragmentation will be conducted at NZP.

Human Dimensions of Global Change

The general public and research communities will be informed of global change research conducted by Smithsonian and other USGCRP agencies via exhibits. During FY 2010, an exhibition on soils developed by staff at NMNH and SERC will continue to be displayed at NMNH. Part of the "Forces of Change" series, the exhibition includes soils' role as a source and sink of atmospheric carbon.

Related Research

Much of the global change research performed at the Smithsonian is not supported by direct Federal appropriation (i.e., USGCRP crosscut funding) and instead is supported by other public and private sources (including other USGCRP-participating agencies). These projects are nonetheless organized around the program elements, thus amplifying the scope and impact of research supported directly by the USGCRP. SAO has extensive measurement programs for stratospheric and tropospheric composition. These include pollution measurement from space and its eventual development into continuous global monitoring. This work contributes to global climate observations, enhances climate-modeling systems, quantifies greenhouse gas sources and sinks, and reduces scientific uncertainties about aerosol effects. There are continuing studies on solar activity and its relationship to climate. SERC and STRI receive agency support via competitive grants programs to perform studies of ecosystem responses to increased carbon dioxide, UV-B radiation, and invasive species. Other contributing activities include research conducted by several units within the Smithsonian in a variety of habitats concerning natural and human-induced variations in species, populations, communities, and ecosystems. These studies help clarify the relative importance of global change effects as one of several agents of ecological change. Studies of environmental change over long time periods are aided by the Institution's collections. Used by researchers around the world, these materials provide raw data for evaluating changes in the physical and biological environment that occurred before human influences.

APPENDIX B

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM FY 2010 BUDGET TABLES

The USGCRP integrates federally supported research on global change and climate change, as conducted by 13 U.S. Government departments and agencies:

- Department of Agriculture (USDA)
- Department of Commerce (DOC)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Health and Human Services (HHS)
- Department of the Interior (DOI)
- Department of State (DOS)
- Department of Transportation (DOT)
- Agency for International Development (USAID)
- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Smithsonian Institution (SI)

USGCRP's budget requests are coordinated through interagency research working groups and other mechanisms, but ultimate budget accountability resides with the participating departments and agencies. As a result of its interagency composition, activities of USGCRP participating agencies are funded by Congress through nine of the 13 annual Appropriations bills. Several agencies and departments fund observations of the global environment for climate change research. With the exception of activities associated with NASA's Earth missions and mission operations whose total amounts are identified in Tables 1, 2 and 3, the climate related observations of the other USGCRP departments and agencies are included in their research budgets.

The following tables summarize the USGCRP budget:

- Tables 1 and 2 show the USGCRP FY 2008-2010 budget aligned by the goals and subgoals from the program's *2003 Strategic Plan*.
- Table 3 shows the USGCRP FY 2008-2010 budget by agency.
- Table 4 shows the USGCRP FY 2008-2010 budget by research element as described in the *2003 Strategic Plan*.
- Subsequent tables show, for each USGCRP participating agency, the FY 2008-2010 budgets listed by agency USGCRP programs or activities.

Table 1. FY 2008-2010 U.S. Global Change Research Program Budget By Goal And Focus Area

Focus Area	Description (from Strategic Plan)	Budgets ($M)[a]			Agency(ies)
		FY08 Actual	FY09[b] Estimate	FY10 Request	
GOAL 1	***Improve knowledge of the Earth's past and present climate and environment, including it natural variability, and improve understanding of the causes of observed variability and changes***				
Focus 1.1	Better understand natural long-term cycles in climate [e.g., Pacific Decadal Variability (PDV), North Atlantic Oscillation (NAO)]	40.8	49.2	52.2	DOC, DOE, DOI, NASA, NSF
Focus 1.2	Improve and harness the capability to forecast El Niño-La Niña and other seasonal-tointerannual cycles of variability	34.6	37.9	36.5	DOC, DOE, NASA, NSF
Focus 1.3	Sharpen understanding of climate extremes through improved observations, analysis, and modeling, and determine whether any changes in their frequency or intensity lie outside the range of natural variability	39.1	49.0	42.4	DOC, DOE, DOI, NASA, NSF
Focus 1.4	Increase confidence in the understanding of how and why climate has changed	42.6	55.5	49.0	DOE, DOI, NASA, NSF, SI
Focus 1.5	Expand observations and data/information system capabilities	193.0	422.1	227.3	DOC, DOE, DOI, NASA, NSF, SI
GOAL 1 TOTAL		**350.1**	**613.7**	**407.4**	
GOAL 2	***Improve quantification of the forces bringing about changes in the Earth's climate and related systems***				
Focus 2.1	Reduce uncertainties about the sources and sinks of GHGs, emissions of aerosols and their precursors, and their climate effects	101.5	114.8	109.1	DOC, DOE, DOI, DOT, NASA, NSF
Focus 2.2	Monitor the recovery of the ozone layer and improve the understanding of the interactions of climate change, ozone depletion, tropospheric pollution, and other atmospheric issues	28.0	27.5	24.8	USDA, DOE, NASA
Focus 2.3	Increase knowledge of the interactions among emissions, long-range atmospheric transport, and transformations of atmospheric pollutants, and their response to air quality management strategies	42.1	44.2	43.7	NASA, NSF
Focus 2.4	Develop information on the carbon cycle, land cover and use, and biological/ecological processes by helping to quantify net emissions of carbon dioxide, methane, and other greenhouse gases, thereby improving the evaluation of carbon sequestration strategies and alternative response options	132.7	153.6	147.0	USDA, DOC, DOE, DOI, NASA, NSF, SI

Focus Area	Description (from Strategic Plan)	Budgets ($M)[a]			Agency(ies)
		FY08 Actual	FY09[b] Estimate	FY10 Request	
Focus 2.5	Improve capabilities to develop and apply emissions and related scenarios for conducting "If…, then…" analyses in cooperation with CCTP	3.0	7.6	9.3	DOE
GOAL 2 TOTAL		**307.2**	**347.6**	**333.8**	
GOAL 3	***Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future***				
Focus 3.1	Improve characterization of the circulation of the atmosphere and oceans and their interactions through fluxes of energy and materials	38.4	51.1	45.6	DOC, DOE, NASA, NSF
Focus 3.2	Improve understanding of key "feedbacks" including changes in the amount and distribution of water vapor, extent of ice and the Earth's reflectivity, cloud properties, and biological and ecological systems	68.4	69.9	72.1	DOE, DOI, NASA, NSF
Focus 3.3	Increase understanding of the conditions that could give rise to events such as rapid changes in ocean circulation due to changes in temperature and salinity gradients	11.9	15.7	17.5	DOE, DOI, NASA,NSF
Focus 3.4	Accelerate incorporation of improved knowledge of climate processes and feedbacks into climate models to reduce uncertainty in projections of climate sensitivity, changes in climate, and related conditions such as sea level	95.6	131.4	121.3	DOC, DOE, DOI, NASA, NSF
Focus 3.5	Improve national capacity to develop and apply climate models	45.5	60.8	51.1	DOC, DOE, DOI, NASA, NSF
GOAL 3 TOTAL		**259.7**	**328.8**	**307.5**	
GOAL 4	***Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related globalchanges***				
Focus 4.1	Improve knowledge of the sensitivity of ecosystems and economic sectors to global climate variability and change	58.4	66.2	70.0	USFA, DOE, DOI, EPA, NASA, NSF, SI
Focus 4.2	Identify and provide scientific inputs for evaluating adaptation options, in cooperation with mission-oriented agencies and other resource managers	12.5	14.9	23.2	HHS, DOI, EPA, NSF
Focus 4.3	Improve understanding of how changes in ecosystems (including managed ecosystems such as croplands) and human infrastructure interact over long periods of time	45.9	52.1	52.4	USDA, DOC, DOI, NASA, NSF, SI
GOAL 4 TOTAL		**116.8**	**133.2**	**145.6**	

Focus Area	Description (from Strategic Plan)	Budgets ($M)[a]			Agency(ies)
		FY08 Actual	FY09[b] Estimate	FY10 Request	
GOAL 5	***Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change***				
Focus 5.1	Support informed public discussion of issues of particular importance to U.S. decisions by conducting researchand providing scientific synthesis and assessment reports	58.7	67.5	55.4	USDA, DOI, EPA, NASA, NSF, SI
Focus 5.2	Support adaptive management and planning for resources and physical infrastructure sensitive to climate variability and change; build new partnerships with public and private sector entities that can benefit both research and decisionmaking	64.0	52.3	77.3	USDA, DOC, DOI, EPA, NASA, NSF, USAID
Focus 5.3	Support policymaking by conducting comparative analyses and evaluations of the socioeconomic and environmental consequences of response options	20.8	30.8	28.0	USDA, DOE, DOI, EPA, NASA, NSF, SI
GOAL 5 TOTAL		**143.5**	**150.6**	**160.7**	
USGCRP Research TOTAL (Sum Goal 1 through Goal 5)		**1177.4**	**1573.9**	**1355.1**	
USGCRP Observations		**655.0**	**866.8**	**669.5**	
USGCRP TOTAL		**1832.4**	**2440.7**	**2024.6**	

[a] Any minor discrepancies within this table and between this table and the others are due to rounding

[b] FY09 amounts include FY09 estimated expenditures and FY09 funds authorized under the American Recovery and Reinvestment Act

Table 2. FY 2008-2010 U.S. Global Change Research Program Budget by Goal and Participating Agency/Department

[Discretionary Budget Authority In $M][a]

Goal	USDA	DOC	DOE	HHS	DOI	DOT	US-AID	EPA	NASA	NSF	SI	Re-search	Obser-vations	TOTAL
FY 2010														
1	0.0	185.5	55.0	0.0	12.4	0.0	0.0	0.0	85.9	67.5	1.1	407.4	328.4	735.8
2	23.0	41.8	39.8	0.0	7.1	2.7	0.0	0.0	134.6	84.5	0.4	333.8	82.4	416.2
3	0.0	50.8	54.6	0.0	7.5	0.0	0.0	0.0	113.6	81.0	0.0	307.5	202.4	509.9
4	24.9	2.1	13.9	4.0	17.0	0.0	0.0	4.4	19.9	54.9	4.5	145.6	56.3	201.9
5	10.7	16.3	2.0	0.0	19.0	0.0	36.0	16.7	47.0	12.0	1.0	160.7	0.0	160.7
Total	**58.6**	**296.5**	**165.3**	**4.0**	**63.0**	**2.7**	**36.0**	**21.1**	**401.0**	**299.9**	**7.0**	**1355.1**	**669.5**	**2024.6**
FY 2009[b]														
1	0.0	305.4	113.6	0.0	11.7	0.0	0.0	0.0	97.1	84.8	1.1	613.7	409.5	1023.2
2	22.9	39.9	36.6	0.0	5.0	2.5	0.0	0.0	148.4	92.0	0.4	347.6	127.8	475.4
3	0.0	58.9	62.7	0.0	4.3	0.0	0.0	0.0	124.4	78.5	0.0	328.8	257.7	586.5
4	23.9	3.9	12.9	4.0	12.1	0.0	0.0	3.8	21.6	47.8	3.2	133.2	71.8	205.0
5	8.9	13.7	6.9	0.0	12.3	0.0	16.9	14.1	64.8	12.0	1.0	150.6	0.0	150.6
Total	**55.7**	**421.8**	**232.7**	**4.0**	**45.4**	**2.5**	**16.9**	**17.9**	**456.3**	**315.0**	**5.7**	**1573.9**	**866.8**	**2440.7**
FY 2008														
1	0.0	165.2	46.4	0.0	11.7	0.0	0.0	0.0	76.2	49.5	1.1	350.1	343.5	693.6
2	21.1	40.3	31.8	0.0	5.2	0.7	0.0	0.0	147.3	60.5	0.4	307.2	116.1	423.3
3	0.0	48.2	34.8	0.0	3.3	0.0	0.0	0.0	123.7	49.7	0.0	259.7	157.2	416.9
4	19.8	4.7	13.1	4.0	8.1	0.0	0.0	4.0	21.9	38.0	3.2	116.8	38.2	155.0
5	24.3	13.7	2.0	0.0	5.7	0.0	14.4	13.4	60.0	9.0	1.0	143.5	0.0	143.5
Total	**65.2**	**272.1**	**128.1**	**4.0**	**34.0**	**0.7**	**14.4**	**17.4**	**429.1**	**206.7**	**5.7**	**1177.4**	**655.0**	**1832.4**

[a] Any minor discrepancies within this table and between this table and the others are due to rounding

[b] FY09 amounts include FY09 estimated expenditures and FY09 funds authorized under the American Recovery and Reinvestment Act

TABLE 3. U.S. Global Change Research Program: FY 2008-2010 Budget by Agency

[Discretionary Budget Authority in $M][a]					
Agency	FY2008 Actual	FY2009			FY 2010 Request
	Program	Enacted	Recovery Act	Total Program	USGCRP[b]
USDA	65	56	0	56	59
DOC	272	369	53	422	297
DOE	128	168	65	233	165
HHS	4	4	0	4	4
DOI	34	45	0	45	63
DOT	1	2	0	2	3
EPA	17	18	0	18	21
NASA	429	419	37	456	401
NSF	207	220	95	315	300
SI	6	6	0	6	7
USAID	14	17	0	17	36
Total Research	**1177**	**1324**	**250**	**1574**	**1356**
NASA Space-Based Observations	**655**	**667**	**200**	**867**	**670**
TOTAL	**1832**	**1991**	**450**	**2441**	
President's Request					**2026**

[a] Any minor discrepancies within this table and between this table and the others are due to rounding

[b] Beginning in FY 2010, USGCRP is the revised designation for the program previously designated as CCSP during the period 2002 through May 2009. USGCRP was the designation for this program from 1990 to 2002.

Table 4. U.S. Global Change Research Program
FY 2010 USGCRP Research Elements
FY 2008-2010 USGCRP Scientific Research Budget By Research Element

[Discretionary Budget Authority in $Millions][a]								
FY 2010 USGCRP Research Elements								
Agency	**Atmospheric Composition**	**Climate Variability**	**Carbon Cycle**	**Water Cycle**	**Ecosys-tems**	**Land Use**	**Human Contributions**	**Total**
USDA	—	—	26.9	6.3	23.0	1.3	1.0	**58.5**
DOC	24.4	238.2	12.1	10.0	2.1	—	9.7	**296.5**
DOE	0.6	123.6	14.1	0.6	14.1	0.6	11.8	**165.4**
HHS	—	—	—	—	—	—	4.0	**4.0**
DOI	—	11.8	11.4	6.6	12.1	4.4	16.7	**63.0**
DOT	2.7	—	—	—	—	—	—	**2.7**
EPA	10.6	—	—	4.3	4.3	—	1.7	**20.9**
NASA	86.6	80.3	53.0	92.5	36.0	19.5	33.2	**401.1**
NSF	28.9	98.4	58.2	33.7	56.7	2.8	21.2	**299.9**
SI	0.1	1.3	0.3	—	4.5	0.8	—	**7.0**
USAID	—	—	—	—	—	—	36.0	**36.0**
Scientific Research Total	**153.9**	**553.6**	**176.0**	**154.0**	**152.8**	**29.4**	**135.3**	**1355.0**
FY 2009 USGCRP Research Elements								
Agency	**Atmospheric Composition**	**Climate Variability**	**Carbon Cycle**	**Water Cycle**	**Ecosys-tems**	**Land Use**	**Human Contributions**	**Total**
USDA	—	—	26.1	5.3	22.0	1.3	1.0	**55.7**
DOC	22.5	365.5	12.1	10.0	2.1	—	9.7	**421.9**
DOE	0.6	188.7	13.6	0.6	13.6	0.6	15.1	**232.8**
HHS	—	—	—	—	—	—	4.0	**4.0**
DOI	—	9.6	7.7	4.9	8.6	3.8	10.9	**45.5**
DOT	2.5	—	—	—	—	—	—	**2.5**
EPA	8.7	—	—	3.8	3.8	—	1.6	**17.9**
NASA	94.3	88.0	57.7	104.3	40.1	22.4	49.0	**455.8**
NSF	31.9	128.7	50.1	31.6	49.5	2.8	20.4	**315.0**
SI	0.1	1.3	0.3	—	3.2	0.8	—	**5.7**
USAID	—	—	—	—	—		16.9	**16.9**
Scientific Research Total	**160.6**	**781.8**	**167.6**	**160.5**	**142.9**	**31.7**	**128.6**	**1573.7**

Table 4 Continued.

[Discretionary Budget Authority in $Millio								
FY 201 SGC Research Elements								
Agency	Atmospheric Composition	Climate Variability	Carbon Cycle	Water Cycle	Ecosys-tems	Land Use	Human Contributions	Total
USDA	17.5	—	22.2	5.4	18.0	1.4	1.0	**65.4**
DOC	23.1	215.9	12.1	9.9	1.5	—	9.7	**272.2**
DOE	0.6	93.7	13.6	0.6	13.6	0.6	5.4	**128.1**
HHS	—	—	—	—	—	—	4.0	**4.0**
DOI	—	9.5	6.4	4.6	5.3	3.9	4.3	**34.0**
DOT	0.7	—	—	—	—	—	—	**0.7**
EPA	7.9	—	—	4.0	4.0	—	1.5	**17.4**
NASA	82.2	87.1	56.7	98.8	43.0	21.6	39.5	**428.9**
NSF	24.2	81.4	43.2	18.4	20.5	2.8	16.2	**206.7**
SI	0.1	1.3	0.3	—	3.2	0.8	—	**5.7**
USAID	—	—	—	—	—	—	14.4	**14.4**
Scientific Research Total	**156.3**	**488.9**	**154.5**	**141.7**	**109.1**	**31.1**	**96.0**	**1177.5**

U.S. Department of Agriculture			
USDA Program Title	**FY 2008 Actual**	**FY 2009 Enacted**	**FY 2010 Request**
Global Carbon Cycle	**21.5**	**25.5**	**26.3**
Agricultural Research Service	3.9	3.9	4.0
Cooperative State Research, Education, and Extension Service	3.0	3.0	3.0
Economic Research Service	0.1	0.7	1.4
Forest Service	7.3	8.3	8.3
Carbon Cycle Research (ARS)	0.6	0.6	0.6
Carbon Cycle Research (FS)	3.5	4.5	4.5
Carbon Inventory and Analysis (FS)	1.1	1.1	1.1
Carbon Management Research (FS)	1.9	3.4	3.4
Water Cycle	**4.7**	**4.7**	**5.7**
Agricultural Research Service	3.3	3.3	4.3
Forest Service	1.4	1.4	1.4
Land Use / Land Cover Change	**0.7**	**0.7**	**0.7**
Cooperative State Research, Education, and Extension Service	0.7	0.7	0.7
Understanding Atmospheric Composition and Chemistry	**17.5**	**0.0**	**0.0**
Agricultural Research Service	17.5	0.0	0.0
Understanding Ecosystems Changes	**17.3**	**21.4**	**22.4**
Agricultural Research Service	11.0	11.1	12.0
Cooperative State Research, Education, and Extension Service	2.7	2.7	2.7
Forest Service	3.6	7.6	7.6
Understanding the Human Dimensions of Climate Change	**1.0**	**1.0**	**1.0**
Cooperative State Research, Education, and Extension Service	1.0	1.0	1.0
Support the UV-B Monitoring Network	**1.6**	**1.4**	**1.4**
Cooperative State Research, Education, and Extension Service	1.6	1.4	1.4
Other National Research Initiative	**1.0**	**1.0**	**1.0**
Regional and Sectoral Impacts of Climate Change (ARS)	1.0	1.0	1.0
USDA Total	**65.3**	**55.7**	
President's Request			**58.6**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding			

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, Department of Agriculture CCSP activities are funded under Title I–Agricultural Programs, within the ARS, CSREES Research and Education Activities, and ERS accounts; and under Title II–Conservation Programs, within the NRCS Conservation Operations account. Also in Appropriations Committee reports, U.S. Department of Agriculture CCSP activities are funded in the USDA FS section under Title II–Related Agencies, within the FS Forest Research account.

U.S. Department of Commerce					
DOC Program Title	FY 2008 Actual	FY 2009			FY 2010 Request
		Enacted	Recovery Act	FY09 Total Program	
NOAA Laboratories and Cooperative Institutes	50.4	46.1	0.0	46.1	49.4
NOAA Competitive Research Program	130.0	132.0	0.0	132.0	144.2
NOAA Climate Data and Information	7.6	8.3	0.0	8.3	12.1
NOAA Climate Operations	0.5	0.9	0.0	0.9	0.9
NOAA Climate Regimes and Ecosystem Productivity	1.5	2.1	0.0	2.1	2.1
NOAA Operational Climate Programs	82.1	174.5	53.0	227.5	82.9
NIST Measurements and Standards for the Climate Change Research Program	0.2	4.9	0.0	4.9	4.9
DOC Total	**272.2**	**368.8**	**53.0**	**421.8**	
President's Request					**296.5**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding					

"Mapping of Budget Request to Appropriations Legislation. In Appropriations Committee reports, funding for National Oceanic and Atmospheric Administration CCSP activities is specified in the Laboratories and Cooperative Institutes, Competitive Research Programs, Climate Operations, and Climate Data and Information lines of the Oceanic and Atmospheric Research budget; in the Climate Regimes and Ecosystem Productivity line of the National Marine Fisheries Service budget; the Data Centers and Information Services line of the National Environmental Satellite, Data, and Information Service (NESDIS) budget; and the Local Warnings and Forecasts and Central Forecast Guidance lines of the National Weather Service (NWS) budget within NOAA's Operations, Research, and Facilities account. In addition, a portion of NOAA's climate funding is found within the Procurement, Acquisition, and Construction account for NESDIS and NWS. Funding for National Institute of Standards and Technology CCSP activities is specified in the Scientific and Technical Research and Services account."

U.S. Department of Energy					
DOE Program Title	FY 2008 Actual	FY 2009			FY 2010 Request
		Enacted	Recovery Act	FY09 Total Program	
Atmospheric System Research	25.2	25.3	0.0	25.3	25.4
Atmospheric Radiation Measurement Infrastructure	37.6	40.3	60.0	100.3	40.8
Terrestrial Ecosystem Science	26.0	25.9	0.0	25.9	26.9
Climate and Earth System Modeling	35.1	72.1	4.9	77.0	68.0
Data Management and Education	4.2	4.2	0.0	4.2	4.2
DOC Total	**128.1**	**167.8**	**64.9**	**232.7**	
President's Request					**165.3**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding					

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, Department of Energy CCSP activities are funded under Title III–Department of Energy, within the Energy Supply, Research, and Development Activities account. Also in these Appropriations Committee reports, funding for Department of Energy CCSP activities is included as part of the appropriation for Biological and Environmental Research.

U.S. Department of Health and Human Services				
HHS Program Title		FY 2008 Actual	FY 2009 Enacted	FY 2010 Request
FIC & NIEHS	Study of Air Pollution Control	0.1	0.1	0.1
NCI	Global change in cancer	0.3	0.3	0.3
NIAID	Climate change and avian borne disease	0.6	0.6	0.6
NICHD	Regional demographic factors related to climate change	1.6	1.6	1.6
NIEHS	Climate change and marine pathogens	1.1	1.1	1.1
NIGMS	Ecological modeling of insect borne disease	0.3	0.3	0.3
USDA Total		**4.1**	**4.1**	
President's Request				**4.1**
Institution FIC Fogarty International Center NCI National Cancer Institute NIAID National Institute of Alergy and Infectuous Disease NICHD National Institute of Child Health and Human Development NIEHS National Institute of Environmental Health Sciences NIGMS National Institute of General Medicine Sciences				
Note: Any minor discrepancies within this table and between this table and the others are due to rounding				

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, Department of Health and Human Services CCSP activities are funded under the National Institutes of Health section of Title II–Department of Health and Human Services.

U.S. Department of the Interior				
DOI Program Title		FY 2008 Actual	FY 2009 Enacted	FY 2010 Request
USGS	Global Change Research & Development	23.4	22.5	24.7
USGS	Climate Impacts Monitoring/Climate Effects Network	2.3	4.0	10.0
USGS	National Climate Change and Wildlife Science Center	1.5	10.0	15.0
USGS	Carbon Sequestration - Biological and Geological Assessments	1.0	3.0	7.0
USGS	Decision Support & Applications	1.0	1.1	1.5
USGS	National Satellite Land Remote Sensing Data Archive	3.7	3.7	3.7
USGS	Biosequestration Data Gap Analysis	1.1	1.1	1.1
USDA Total		**34.0**	**45.4**	
President's Request				**63.0**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding				

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, Department of the Interior CCSP activities are funded under Title I–Department of the Interior. Funding for U.S. Geological Survey CCSP programs is included within the USGS Survey, Investigations, and Research account.

U.S. Department of Transportation			
DOT Program Title	FY 2008 Actual	FY 2009 Enacted	FY 2010 Request
Partnership for Air Transportation Noise and Emissions Reduction (PARTNER)	0.3	0.5	0.5
NextGen – Aviation Climate Change Research Initiative	0.0	1.5	1.9
Aviation Environmental Design Tool (AEDT) & System for Assessing Global Emissions (SAGE)	0.3	0.2	0.2
DOT – wide Climate Change Center – (disbursements in millions)	0.2	0.3	0.2
USDA Total	**0.7**	**2.5**	
President's Request			**2.7**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding			

Mapping of Budget Request to Appropriations Legislation. Since 2000, the Department's climate change research has been funded by contributions from eight of DOT's operating administrations and the Office of the Secretary.

U.S. Agency for International Development				
		FY 2008 Actual	FY 2009 Enacted	FY 2010 Request
FEWS NET	Famine Early Warning System Network	13.5	16.1	18.0
SERVIR	Regional visualization and monitoring system	0.9	0.8	18.0
USDA Total		**14.4**	**16.9**	
President's Request				**36.0**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding				

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, U.S. Agency for International Development CCSP activities are funded under Title II–Bilateral Economic Assistance: United States Agency for International Development.

U.S. Environmental Preotection Agency			
EPA Program Title	FY 2008 Actual	FY 2009 Enacted	FY 2010 Request
Air quality research and assessment	7.9	8.7	10.6
Research and assessments of the integrated effects of global change	1.5	1.6	1.7
Water quality/aquatic ecosystems research and assessment	8.0	7.6	8.6
USDA Total	**17.4**	**17.9**	
President's Request			**20.9**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding			

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, Environmental Protection Agency CCSP activities are funded under the EPA section of Title III–Independent Agencies, within the Science and Technology account. Appropriations Committee report language may specify more directly the funding for global change research.

U.S. National Aeronautics and Space Administration					
NASA Program Title	**FY 2008 Actual**	**FY 2009**			**FY 2010 Request**
		Enacted	**Recovery Act**	**FY09 Total Program**	
Atmospheric Composition	82.2	84.3	10.0	94.3	86.6
Climate Variability	87.1	81.5	6.5	88.0	80.3
Carbon Cycle	56.7	53.3	4.4	57.7	53.0
Water Cycle	98.8	99.2	5.1	104.3	92.5
Ecosystems	43.0	35.5	4.6	40.1	36.0
Land Cover Land use Change	21.6	19.9	2.5	22.4	19.5
Human Contributions and Responses	39.5	44.9	4.1	49.0	33.2
Scientific Research Sub-Total	**428.9**	**418.6**	**37.2**	**455.8**	**401.1**
Atmospheric Composition	68.7	64.1	20.1	84.2	56.2
Climate Variability	188.5	189.8	107.3	297.1	184.8
Carbon Cycle	119.2	93.4	10.7	104.1	77.3
Water Cycle	173.6	206.4	39.1	245.5	237.3
Ecosystems	47.3	51.3	9.0	60.3	50.3
Land Cover Land use Change	57.7	62.2	13.3	75.5	63.6
Space-Based Observations Sub-Total	**655.0**	**667.2**	**199.5**	**866.7**	**669.5**
NASA Total	**1083.9**	**1085.8**	**236.7**	**1322.5**	
President's Request					**1070.6**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding					

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, National Aeronautics and Space Administration CCSP activities are funded under NASA Earth science and technology programs within Title III–Independent Agencies, as part of the Science, Aeronautics, and Technology account.

U.S. National Science Foundation					
NSF Program Title	**FY 2008 Actual**	**FY 2009**			**FY 2010 Request**
		Enacted	**Recovery Act**	**FY09 Total Program**	
Atmospheric Composition	24.2	24.3	7.6	31.9	28.9
Climate Variability and Change	81.4	88.6	40.1	128.7	98.4
Carbon Fluxes & Carbon Cycle	43.2	43.2	6.9	50.1	58.2
Water Cycle	18.4	23.7	7.9	31.6	33.7
Terrestrial & Marine Ecosystems	20.5	20.8	28.7	49.5	56.7
Land Use / Land Cover	2.8	2.8		2.8	2.8
Human Dimensions of Climate Change	16.2	16.2	4.2	20.4	21.2
NSF Total	**206.7**	**219.6**	**95.4**	**315.0**	
President's Request					**299.9**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding					

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, National Science Foundation CCSP activities are supported under the NSF section of Title III–Independent Agencies within the NSF Research and Related Expenses account.

Smithsonian Institution				
SI Program Title		FY 2008 Actual	FY 2009 Enacted	FY 2010 Request
NMNH	Archaebiology Program (Human Ecology History)	0.3	0.3	0.3
NMNH	Paleoecological Effects of Climate Change, including Evolution of Terrestrial Ecosystems	0.9	0.9	0.9
NMNH	Global Volcanism Program	0.2	0.2	0.2
NMNH	Human Origins Program (Human Ecological History)	0.3	0.3	0.3
NMNH	Nile Delta Subsidences/Sea Level Rise	0.2	0.2	0.2
NMNH	Tropical Biodiversity Program	0.6	0.6	0.6
SERC	Ecological effects of ultraviolet radiation	0.2	0.2	0.2
SERC	Effects of increasing atmospheric CO_2 on ecosystems	0.3	0.3	0.3
STRI	Temperate and Tropical Forest Canopy Biology	0.4	0.4	0.4
STRI	Tropical Forest Science	0.9	0.9	2.2
STRI	Biodynamics of Forest Fragments	0.1	0.1	0.1
STRI	Tropical Agroforestry	0.2	0.2	0.2
NZP	Migratory Birds	0.3	0.3	0.3
NZP	Predicting Species Responses	0.7	0.7	0.7
NZP	Monitoring and Assessment of Biodiversity (MAB) Program	0.1	0.1	0.1
SI Total		**5.7**	**5.7**	
President's Request				**7.0**
Note: Any minor discrepancies within this table and between this table and the others are due to rounding				

Mapping of Budget Request to Appropriations Legislation. In the Appropriations Committee reports, Smithsonian Institution CCSP activities are funded in the Smithsonian section of Title II–Related Agencies, within the Salaries and Expenses account. Appropriations Committee reports specify funding for a Sciences line item component of this account, which includes CCSP programs.